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MACHINING AND GRINDING OF ULTRAHIGH-STRENGTH STEELS AND STAINLESS STEEL ALLOYS

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MACHINING AND GRINDING OF ULTRAHIGH-STRENGTH STEELS AND STAINLESS STEEL ALLOYS

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ABSTRACT

This report covers the state of the art of metal-removal operations for stainless and ultrahigh-strength steels. It describes the methods currently employed for conventional machining, grinding, electrolytic, electric-discharge, and chemical-machining processes. The precautions that should be taken to avoid troubles resulting from the characteristics typical of these alloys are pointed out. Nine machining, two grinding, two cutting, and three unconventional metal-removal operations are discussed separately. Other sections discuss the classification of these alloys and their general response to machining variables.

FOREWORD

Precipitation-hardening stainless steels are potentially useful wherever corrosion resistance and high strength at high temperatures are needed. They were developed initially to meet urgent requirements in World War II, but new alloys and methods of processing have since been introduced to assist engineers concerned with missiles and space vehicles and with various applications in the field of nuclear science and technology.

The Atomic Energy Commission and National Aeronautics and Space Administration have established a cooperative program to make available information, describing the technology resulting from their research and development efforts, which may have commercial application in American industry. This publication is one of the many resulting from the cooperative effort of these agencies to transfer technology to private industry.

This survey is based on information contained in a series of reports originally prepared by Battelle Memorial Institute for the Manufacturing Engineering Laboratory of the George C. Marshall Space Flight Center. The original information has been updated and revised in writing the current, seven volume survey. These volumes were prepared under a contract with the NASA Office of Technology Utilization which was monitored by the Redstone Scientific Information Center.

PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report on practices used for removing metal from high-strength and stainless steels is intended to provide information useful to designers and fabricators. The detailed recommendations are considered to be reliable guides for selecting conditions, tools, and equipment suitable for specific operations. The causes of common problems are identified and precautions for avoiding them are mentioned.

The report summarizes information collected from manufacturers' handbooks, technical books and publications, reports on Government contracts, and by personal contacts with engineers associated with specialized companies. A total of 137 references, most of them covering the period since 1960, are cited. Detailed data available prior to 1961, mostly on high-strength steels, were covered by DMIC Memorandums 30, 31, and 58 issued by the Defense Metals Information Center. A large part of the more recent information originated from a systematic search of Government reports and technical papers.

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MACHINING AND GRINDING OF ULTRAHIGH-STRENGTH STEELS AND STAINLESS STEEL ALLOYS

SUMMARY

Nonstainless alloy steels and stainless steel alloys generally do not machine as well as mild steels. Machining problems originate from their higher strengths, and the increased propensity of the austenitic-type alloys to work harden during machining. The harder chips produced are abrasive to tools and, hence, accelerate tool wear.

These alloyed steels also exhibit reduced thermal diffusivities. The high-strength low-alloy steels and die steels, for example, possess about 50 to 70 percent of the thermal diffusivity of carbon steel. The various stainless steel compositions, on the same basis, show a value of 50 percent for Type 410, and as low as 23 percent for A-286.

The overall consequence of increased strengths and lower thermal diffusivities is a higher tool-chip interface temperature than would occur when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided. Excessive temperatures also lead to welding and tool buildup, which in turn increases friction and produces poor surface finishes.

These difficulties can be minimized by following recommendations given in this report. The use of relatively low cutting speeds along with the suggested cutting fluids will reduce buildup, friction, and tool-chip temperatures. Work hardening is minimized by using sharp tools of approved geometries. Furthermore, tools should cut, not push metal, and they should never dwell or rub in the cut. When proper techniques are employed, machining of high-strength steels and stainless steels can be successfully accomplished.

INTRODUCTION

The technology of high-speed aircraft and missiles has placed severe demands on materials of construction. In an attempt to meet these requirements, improvements have been made in the compositions of high-strength steels and stainless steel alloys, as well as in fabrication practices.

Materials possessing combinations of high strength, strength stability at elevated temperatures, and corrosion resistance are being specified for many components to improve overall product quality and capability. The jet engine, for example, has made widespread use of both ferrous and nonferrous high-temperature alloys. These materials, along with the high-strength steels are also going into airframe structures because of the high stresses and temperatures involved in high-speed flight.

This advanced experience of the aerospace industry is now being utilized in the commercial field. Automotive, transportation, and other commercial enterprises are also concerned with weight, strength, and reliability. Consequently, increasing numbers of industrial companies are considering the advantages that the improved material properties, now available, can provide for their products.

It seems almost axiomatic, however, that improvements in material capabilities often reduce the machining rate of the base material. Consequently, in planning machining operations for these materials, the production engineer must utilize the best machining practices available. If not, he soon becomes aware that the fracture-type chip characteristic of ultrahigh-hardness martensitic steels can lead to chatter, premature tool breakage, and spoiled parts. He also learns that the austenitic and semiaustenitic stainless steels show marked propensities to work harden, especially when machined in the annealed or solution-treated condition. Consequently, he realizes that exacting precautions are necessary in order to machine these materials with any degree of success.

This report presents current information on mechanical and nonmechanical machining operations for the ultrahigh-strength steels and various stainless steel alloys.*,** It describes their individual

*See Appendix for classification and names of the high-strength steels and their key alloy groups.
**Other NASA Technical Memorandums are available and describe machining recommendations for the nickel-base and cobalt-base alloys, and the various titanium alloys.

machining behaviors and arranges the various alloys into major machinability groups.* It also describes the setup conditions needed for specific operations. It should be pointed out, however, that the cutting conditions suggested are intended to serve as guides or starting points for subsequent adjustment to existing plant conditions, available machine tools, and the machining requirements for the parts involved.

Novel nonmechanical methods of machining also have been utilized on difficult-to-machine materials. The latter part of this report deals with three specific methods; namely, electrochemical machining (ECM), chemical machining, and electric-discharge machining (EDM). These machining processes work independently of material hardness and involve no tool-to-work contact. This situation makes these methods exceptionally suitable for machining ultrahard, complex, or fragile parts.

MACHINING BEHAVIOR

The machining behavior of nonstainless alloy steels is different from that of the stainless steel alloys. The reasons include differences in ductilities, galling tendencies, work-hardening rates, and heat-transfer properties (Ref. 1). Differences in machinability also can occur within the nonstainless category because of different microstructures; and within the stainless category because of differences in the work-hardening capabilities of the martensitic and austenitic grades.

Table I shows in a general way the relative difficulty of machining the various alloy steels and stainless steels compared with other metals and alloys. All values are based on resulfurized steel, B-1112, as the standard of comparison (Refs. 2-7).

Machinability ratings of nonstainless alloy steels and Type 410 stainless steel at hardness levels near 350 Bhn are shown in Table II. These hardness levels are sometimes used when machining critical parts to nearly final dimensions prior to final machining (or grinding) the same parts reheat treated to 500 Brinell hardness.

*See Appendix for classification of high-strength steels and key alloy groups.

TABLE 1. TYPICAL MACHINABILITY RATINGS OF SELECTED ALLOY STEELS STAINLESS STEEL ALLOYS, AND OTHER ALLOYS (REFS. 2-7)

Alloy	Type	Condition[a]	Rating[b]
Aluminum	2017	T4	300
Resulfurized steel	B-1112	HR	100
Carbon steel	1020	CD	70
Low-alloy steel (Cr-Mo)	A-4130	Ann and CD	70
Low-carbon stainless steel	405, 403	Ann	60
Ferritic stainless steel	430	Ann	55
Martensitic stainless steel	410	Ann	55
Low-alloy steel (Cr-Ni-Mo)	A-4340	Ann and CD	50
Stainless steel (400 Series)	442, 431	Ann and CD	50
Hot-work die steel (5Cr-Mo-V)	H-11	Ann	45
Austenitic stainless steel	304	Ann	45
Maraging steel	18Ni-Co-Mo	Ann	40
Austenitic stainless steel	347	Ann	40
Titanium	Commercially pure	Ann	40
Stainless steel superalloy (austenitic; NPH)	19-9 DL	Ann and CD	35
Semiaustenitic stainless steel (PH)	17-7 PH	Ann	35
Stainless steel superalloy (austenitic; PH)	A-286	Ann	25
Titanium alloy	Ti-6Al-4V	Ann	22
Hastelloy alloy	C	Ann	20
Inconel alloy	X-750	STA	15
Haynes alloy	HS-25	Ann	10
René alloy	41	STA	6

(a) T4 = solution treated and artificially aged
HR = hot rolled
Ann = annealed
STA = solution treated and aged
CD = cold drawn.

(b) Based on AISI B1112 steel as 100 using cutting speeds that would result in equal tool lines. Higher numbers indicate better machinability.

TABLE II. APPROXIMATE MACHINABILITY RATINGS OF LOW-ALLOY STEELS AND DIE STEELS IN THE HARDENED CONDITION (REF. 2)

Steel	Type	Condition[(a)]	Rating[(b)]
Low-alloy steel (Cr-Mo)	A-4130	Q and T (350 Bhn)	30
	UHS-260	Q and T (350 Bhn)	30
	Chromalloy	Q and T (350 Bhn)	25
	17-22-AS	Q and T (350 Bhn)	20
Low-alloy steel (Cr-Ni-Mo)	A-4340	Q and T (350 Bhn)	25
	Super Tricent	Q and T (350 Bhn)	25
	A-4340	Q and T (500 Bhn)	10
Hot-work die steel (5Cr-Mo-V)	Vascojet 1000	Q and T (350 Bhn)	30
	Unimach II	Q and T (350 Bhn)	28
	Peerless 56	Q and T (510-540 Bhn)	10
Martensitic stainless steel	Type 410	Q and T (350 Bhn)	25

(a) Q and T = quenched and tempered.
(b) Based on AISI B-1112 steel as 100.

EFFECT OF PROPERTIES ON MACHINABILITY

There are several underlying reasons for the reduced machinabilities of alloy and stainless steels when compared with carbon steels. First, they are harder and stronger, as indicated in Table III. Second, the austenitic-type alloys are strain hardened more during machining by the plastic deformation occurring simultaneously in the chips and surface layer of the workpiece. Harder chips are more abrasive and hence accelerate tool wear. Figure 1 illustrates these work-hardening capabilities by comparing the effects of deformation on the hardness of several metals differing in composition and initial hardness (Ref. 8).

Cutting Forces. The original properties of the workpiece and those developed during machining control the cutting forces on the tool and hence the power to overcome them. Low-alloy steels heat treated to 350 Brinell hardness require 1.2 to 1.5 hp/cu in./min, and stainless steels between 1.4 and 1.5 hp/cu in./min to overcome the opposing cutting forces. Low-alloy steels and 5Cr-Mo-V die steels heat treated to 500 Brinell hardness require 2 to 2.2 hp for each cubic inch of metal removed per minute. These values are in contrast to about 0.8 hp for carbon steels (Refs. 16, 28-30).

TABLE III. MECHANICAL PROPERTIES AND MACHINABILITY RATINGS FOR CERTAIN STEELS AND HIGH-TEMPERATURE ALLOYS (REFS. 9-27)

Alloy	Condition[a]	Strength, 1000 psi		Elongation, percent	Machinability Rating	Horsepower, hp/cu in. /min
		Tensile	Yield			
		Carbon Steels				
B-1112 steel	HR	56	33	25	100	0.23-0.36
1020 steel	CD	61	51	15	70	0.8 -0.9
		Nonstainless Alloy Steels				
A-4130 steel	Ann	88	60	30	70	0.84-0.94
A-4340 steel	Ann	90	70	23	50	0.84-0.94
Vascojet 1000	Ann	94	51	34	45	0.96-1.23
		Martensitic Stainless Steels				
Type 410 stainless	Ann	75	40	35	45	0.97-1.35
		Austenitic Stainless Steels				
Type 304 stainless	Ann	85	35	60	40	0.97-1.35
Type 347 stainless	Ann	90	35	55	40	0.97-1.35
19-9 DL stainless	Ann	102	42	53	35	--
17-7 PH stainless	Ann	130	40	35	30	1.4
A-286 stainless	ST	91	37	47	25	1.5
		Heat-Treated Material				
A-4130 steel	Q and T (350 Bhn)	170	140	15	30	1.5
A-4340 steel	Q and T (350 Bhn)	180	163	15	25	1.5
Vascojet 1000	Q and T (350 Bhn)	180	150	15	30	1.5
Type 410 stainless	Q and T (390 Bhn)	190	145	15	25	1.4
17-7 PH stainless	STA (38 R_C)	180	150	6	--	--
A-286 stainless	STA (300 Bhn)	146	100	25	20	1.5

(a) T4 = solution heat treated and artifically aged
HR = hot rolled
Ann = annealed
STA = solution treated and aged
CD = cold drawn
Q and T = quenched and tempered.

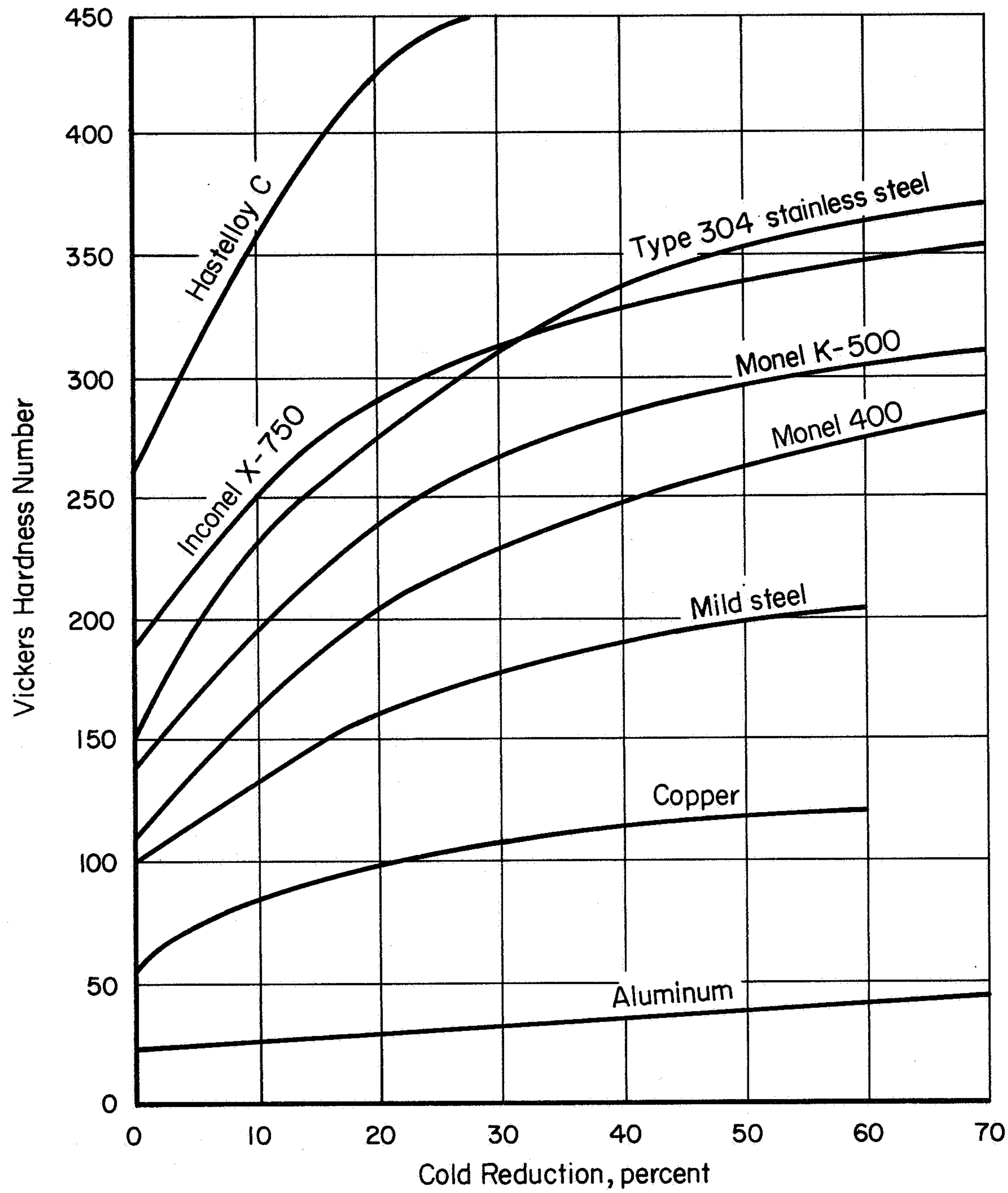


FIGURE 1. EFFECT OF COLD REDUCTION ON HARDNESS INDICATING WORK-HARDENING CAPABILITY

Cutting Temperatures. One of the most damaging conditions for a cutting tool is excessive cutting temperature, and about 95 percent of the energy expended in machining is converted into heat. Other factors being equal, the increase in temperature at the cutting zone is related to the cutting forces and energy requirements. However, the temperatures at the tool point also depend on the rate at which heat is removed by the chip, the cutting fluid, and by conduction through the tool and workpiece.

The heat-transfer characteristics of a material depends on thermal diffusivity, a function of density; specific heat; and thermal conductivity. Austenitic-type alloys exhibit poor thermal diffusivities, as indicated in Table IV; hence, tool-chip interface temperatures are higher than they would be when machining other metals at equal tool stresses. The higher temperatures in the cutting zone lead to rapid tool failure unless efficient cooling is provided by suitable cutting fluids (Refs. 28,31).

The tendency to develop higher cutting temperatures during machining of austenitic-type alloys has several effects. It accelerates tool wear by lowering the strength of cutting tools (Refs. 28,31). It also promotes chemical reactions and seizing, which increase friction and cause chips to form a built-up edge on the tool. Furthermore, the built-up edge periodically sloughs off to give a poor surface finish to the workpiece. The use of lower cutting speeds and better cutting fluids will reduce energy requirements and tool-chip temperatures. Expedients that minimize plastic-deformation effects during machining are also desirable.

Work hardening can be minimized by using short, polished tools, larger (positive) rake angles to promote cutting instead of flow, and larger relief angles to prevent rubbing. Tools should not be allowed to dwell in the cut or to produce glazed or burnished surfaces. Unusually light feeds and cut depths should be avoided. Some investigators recommend machining the heat-treatable alloys in the aged or partially aged conditions to avoid work-hardening effects. For the same reason, cold-drawn and stress-relieved stock is often preferred in alloys that are not hardenable by heat treatment. These aspects are discussed more fully in the following section.

TABLE IV. PHYSICAL PROPERTIES AND RELATIVE HEAT-TRANSFER PROPERTIES OF NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS, 7075 ALUMINUM ALLOY, AND AISI 1020 STEEL (REFS. 12, 15, 20, 21, 25)

Property	7075 Age-Hardened Aluminum Alloy	AISI 1020 Steel	Nonstainless Steels: 4130 and 4340	Nonstainless Steels: 5Cr-Mo-V	Stainless Steels: Type 410	Stainless Steels: Type 304	Stainless Steels: Type 19-9 DL	A-286
Density, ρ, lb/in.^{3}	0.101	0.290	0.283	0.281	0.28	0.29	0.287	0.287
Thermal Conductivity, k, Btu/ft^2 hr °F in.	845	390	264	199	173	113	94	88
Specific Heat C, Btu/lb °F	0.21	0.117	0.114	0.11	0.11	0.12	0.10	0.11
Volume Specific Heat ρC, Btu/in.^{3} °F	0.021	0.034	0.032	0.031	0.031	0.033	0.029	0.032
Thermal Diffusivity, $\frac{k}{\rho C}$	39,800	11,500	8250	6410	5580	3425	3240	2750
Machinability Rating	300	70	70-50	45	45	40	35	25

MACHINING CHARACTERISTICS OF ALLOY AND STAINLESS STEELS

The nonstainless alloy steels usually do not present machining problems in the annealed state (240-300 Bhn). They have a uniform structure with sufficient ferrite for easy tool penetration, and sufficient carbide phase to clear the tool of any ferrite buildup (Ref. 2). In the case of annealed maraging steels, the martensite structure is reasonably ductile, and no unusual machining problems are present (Refs. 32,33).

As the hardness increases, however, metal removal becomes progressively more difficult. A transition from a ductile- to a fracture-type chip occurs, and this ultimately leads to chatter. Cutting loads also increase and tool breakage starts to become a problem. Eventually, the production engineer faces a stringent set of conditions at very high hardnesses (500 Bhn and greater) where only a small latitude separates success and failure (Ref. 2). Consequently, major metal-removal operations are done when these steels are in the annealed condition.

The machinabilities of annealed martensitic and ferritic grades of stainless steel approximate the machinability of annealed AISI 4340, in fact, their microstructures are not unlike those of other steels. In the soft annealed condition their structures consist of lamellae or fine particles of carbide more or less evenly distributed through a ground mass of chromium ferrite. For martensitic stainless steels in the hardened condition, the structure consists of fewer lamellae of carbide evenly distributed in a ground mass of martensite. The straight chromium stainless steels can be cold worked with about the same ease and at about the same rate as carbon steels of similar hardness or tensile strength (Ref. 34). Hence, the feeds and speeds normally used for the low-alloy steels can be adopted as a first approximation for the ferritic and martensitic stainless steels.

Ferritic and martensitic stainless steels, however, are tougher, more ductile, and sometimes stronger than the Cr-Mo low-alloy engineering steels in their most machinable condition. Hence, more power will be needed to perform a given machining operation. There is also an increased tendency for these stainless steels to build up on the cutting edges and radii of the tool, especially in the case of the ferritic grades. Furthermore, the chip itself is brittle and stringy. Short chips, however, can be encouraged by reducing ductility through the use of cold drawing and heat treatment.

The machinabilities of the austenitic stainless steels are generally lower than the steels described above. These steels have a tenacious quality that produces a "gummy" reaction during chip formation. This characteristic plus the high work-hardening rate of these steels produces a strong, tough, stringy chip that is difficult to break. Better results are sometimes obtained in conventional stainless steels when they are annealed and slightly cold worked. This imparts brittleness to the chip, a much needed advantage with these tough, ductile materials (Ref. 35).

Heat treatment can improve the machinability of the semi-austenitic steels like the AM-350 or AM-355 types. In the annealed condition, these steels are soft, and great care must be exercised to prevent any cold work that would induce transformation to martensite. Such transformation would result in erratic machinability and poor tool life (Ref. 36). These steels, however, can be heat treated to the martensitic state, thereby eliminating, to a large extent, the work-hardening problems encountered with fully austenitic structures (Ref. 35). An equalized and overtempered condition has been suggested as providing the best machinability. The equalizing treatment (1450 F for 3 hours, air cooled) involves precipitating the alloy carbides, and transforming the austenite to martensite. The overtemper treatment (1050 F for 3 hours, air cooled) softens the martensite (Ref. 36). Even when heat treated for best machinability, these materials have a hardness of approximately 35 R_C, a rather difficult-to-machine condition in any grade of steel (Ref. 35).

For best machinability, the work-hardenable stainless steel superalloys, such as 19-9 DL, are annealed, cold drawn a controlled amount, and then stress relieved. The warm-worked and stress-relieved condition is the next best. Average machinability can be attained by an intermediate annealing heat treatment. This type of alloy has its poorest machining characteristics in the fully annealed condition (Ref. 36).

The precipitation-hardenable stainless steel superalloys such as A-286 are best machined after being solution treated and cold drawn. Solution treating followed by overaging results in only average machinability. If it is not feasible to overage, the standard solution-treatment and aging cycle will give fairly satisfactory results. Because of gumminess and work-hardening tendencies, the solution-treated condition represents the poorest machining condition for this type of alloy (Ref. 36).

GENERAL MACHINING REQUIREMENTS

The difficulties inherent in machining nonstainless alloy steels and stainless steel alloys can be minimized considerably by providing the proper cutting environment. The basic requirements include rugged machine tools in good condition; vibration-free, rigid setups; high-quality cutting tools, and suitable speeds; feeds; and cutting fluids (Refs. 16,29,31,37-39).

Machine Tools. Machine tools used for cutting these steels need the following characteristics to insure rigid, vibration-free operation (Ref. 40):

(1) Dynamic balance of rotating elements

(2) True running spindle

(3) Snug bearings

(4) Rigid frames

(5) Wide speed/feed ranges

(6) Ample power to maintain speed

(7) Easy accessibility for maintenance.

Milling machines and lathes also should possess backlash elimination devices, and snug, clean, correctly lubricated gibs and slides (Ref. 16).

Vibration Effects. Vibration-free operation is favored by eliminating excessive play in power transmissions, slides, and screws of machine tools (Ref. 40). Undersized or underpowered machines should be avoided. Locating machines near or adjacent to heavy traffic also can induce undesirable vibration and chatter during machining. Last, but not least, insufficient cutter rigidity and improper tool geometry can contribute to vibration and chatter (Refs. 36,39,40).

Rigidity Considerations. Rigidity is a prime requirement since it can mean the difference between success and failure with ultrahigh-hardness steels and highly work-hardenable stainless steel alloys (Ref. 29). It is achieved by using stiff tool-toolholder systems, and adequate clamps or fixtures to minimize deflection of the workpiece and tool during machining.

In milling operations, large-diameter arbors with double arm supports; short, strong tools; rigid holding fixtures; frequent clamping; and adequate support of thin walls and delicate workpieces are desirable (Ref. 39).

Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, using a short tool overhang, and providing steady or follow rests for slender parts (Ref. 40).

Drilling, tapping, and reaming require short tools, positive clamping, and backup plates on through holes (Refs. 39,40).

Cutting-Tool Requirements. High-quality cutting tools are needed for all machining operations. They should be properly ground and finished. The face of the tool should be smooth, and the cutting edges sharp and free of burrs (Ref. 39). Sharp tools help to assure a positive cut and to lessen the work-hardening response (Ref. 36).

Cutting edges should combine proper balance of toughness, hot strength, and abrasion resistance required for the alloy being machined. Since the shear strengths of most hardened alloy steel and stainless steel alloys are much higher than those of plain-carbon steels, the edge strength must be sufficient to support the cutting loads involved. Toughness of a tool is usually balanced against the hardness requirements, although high red hardness is usually needed to retain abrasion resistance at metal-cutting temperatures (Ref. 7).

Milling cutters, drills, and taps should be mounted to run true. Lathe tools usually should cut on dead center. In a multiple-tooth cutter such as a mill or a drill, all teeth should cut the same amount of metal.

Tool Materials. One of the critical decisions in a metal-cutting system is choosing the cutting-tool materials (Ref. 41). Tool materials adequate for machining conventional constructional materials such as carbon steel are not necessarily satisfactory for hardened alloy steels and stainless steels.

At the risk of oversimplification, tool materials of high-speed steel, cast alloy, and carbide are all alike to the extent that they contain hard, brittle refractory carbide particles held in a lower melting metallic matrix. The major difference lies in the amount of carbide present, since the matrix phase of the various materials have similar melting points and, in general, are quite strong and relatively tough. High-speed steels, with the lowest carbide volume, are the toughest but also the least wear resistant. The cemented carbides, having high abrasion resistance but reduced toughness, lie at the opposite end of the scale. The cast alloys occupy an intermediate position (Ref. 42).

Carbide, cast alloy, or high-speed steel cutting tools can be used when machining alloy and stainless steels. Ceramic tools are suitable for ultrahigh-strength steels. The choice depends on seven basic factors:

(1) Condition of the machine tool

(2) Rigidity of the system

(3) Type of cut

(4) Surface condition of the workpiece

(5) Amount of metal to be removed

(6) Metal-removal rate

(7) Desired tool life.

Carbide Tools. Carbide cutting tools are used for high-production items, extensive metal-removal operations, and scale removal. The so-called nonferrous or cast-iron grades of carbides are normally preferred for the stainless steel alloys. These have been identified as CISC Grades C-1 to C-4 inclusive by the Carbide Industry Standardization Committee. The steel grades, C-5 to C-8, are used for the nonstainless alloy steels. A partial list of companies producing these grades of carbide cutting tools is given in Table V.

Competitive brands of cutting tools classified as belonging to the same grade are similar but not identical. Variations in life should be expected from tools produced by different manufacturers and between lots made by the same producer. For this reason, some aircraft companies specify their own lists of interchangeable carbide tools made by approved manufacturers.

TABLE V. TOOL-MATERIAL GUIDE FOR CARBIDES

CISC[b] Grade	Partial List of Carbides[a] Made by Various Manufacturers: Adamas	Carmet	Carboloy	Firth Loach	Firthite	Kenna-metal	Newcomer	Sandvik Coromant	Talide	Tungsten Alloy	Valenite	VR/Wesson	Willey
C-1	B	CA3	44A	FA5	H	K1	N10	H20	C89	9	VC1	2A68, VR54	E8, E13
C-2	A	CA4	883, 860	FA6	HA	K6	N20	H1P	C91	9H	VC2	2A5, VR54	E6
C-3	AA	CA7	905	FA7	HE	K8	N30	H1P	C93	9C	VC3	2A7	E5
C-4	AAA	CA8	999	FA8	HF	K11	N40	H05	C95	9B	VC4	2A7	E3
C-5	DD	CA51	78C	FT3	TQA	KM	N50	S6	S88	11T	VC5	EE, VR77	945
C-5A	43A	CA610	370	FT41, FT5	TXH	K21	--	S1P	S88X	9S	VC125	VR77, VR75	8A
C-6	D	CA609	78B	FT4	TXH, TA	K2S	N60	--	S90	10T	VC6	VR75	710
C-7	C	CA608	78	FT6	TXL	K5H	N70	S1P	S92	8T	VC7	E, VR73	606
C-7A	548	CA606	350	FT61	T16, TAL	K4H	--	--	S92X	5S	--	VR73	6A
C-8	CC	CA605	330	FT7	T31, WF	K7H	N80	F02	S94	5S	VC8	EH	509, 4A

(a) For the same CISC grade, there seem to be no truly equivalent carbides of different brands. Where two carbide grades from the same manufacturer are shown for the same CISC grade, the first is sometimes recommended.

(b) Carbide Industry Standardization Committee.

Notes: (1) The following chip-removal applications have been used for the CISC grade indicated. It will be noted that some grades specify the type of metal removal for which they are best suited.

C-1 Roughing Cuts – cast iron and nonferrous materials
C-2 General Purpose – cast iron and nonferrous materials
C-3 Light Finishing – cast iron and nonferrous materials
C-4 Precision Boring – cast iron and nonferrous materials
C-5 Roughing Cuts – steel
C-5A Roughing Cuts and Heavy Feeds – steel
C-6 General Purpose – steel
C-7 Finishing Cuts – heavy feeds – steel
C-7A Finishing Cuts – line feeds – steel
C-8 Precision Boring – steel

(2) This chart can function only as a guide. The so-called "best grade" may differ for each specific job even if the material being machined is the same. The final selection can be made only by trial and error. Instructions regarding the specific use and application of any competitive grade should be obtained directly from the manufacturer.

Carbide tools require heavy-duty, amply powered machine tools, and vibration-free tool-work setups to prevent chipping. If these basic conditions cannot be met, then high-speed steel tools give better results.

High-Speed Steel Tools. High-speed steel tools can be employed at lower production rates. Tool life is low by conventional standards.

Both the tungsten and molybdenum types of high-speed steel are used. The high hot hardness of tungsten high-speed steels results from the resistance to softening of tempered martensite by precipitation and coalescence of tungsten carbides at elevated temperatures. Molybdenum carbides, as found in molybdenum high-speed steel, dissolve more readily in austenite than do tungsten carbides, but show somewhat greater tendencies to precipitate at tempering temperatures. Most molybdenum high-speed steels utilize both tungsten and molybdenum in suitable ratios to obtain the advantages of both elements.

Cobalt is often added to both tungsten and molybdenum high-speed steels to increase their hardness at temperatures above 1000 F. If this temperature is exceeded much ordinary high-speed steels become too soft to cut effectively. Figure 2 shows this loss in hardness as the temperature rises. It also shows that the cobalt grades exhibit the best hot-hardness values at temperatures above 850 F.

The high-vanadium high-speed steels are also effective above 850 F. These steels contain much more carbon than do the conventional grades. The use of higher carbon levels is made possible by increasing the vanadium content to maintain a specific ratio. This results in fine carbides that greatly increase wear resistance with little loss in toughness (Ref. 43). The high-vanadium T15 grade, and the ultrahard high-speed steels of R_C 70 (AISI M41 to M44) are reputed to be harder than the tough grade of cemented carbide (Ref. 43).

Certain precautions must be observed, however, when the cobalt grades, high-vanadium grades, or the ultrahard high-speed steels are used. They are sensitive to checking and cracking from abrupt temperature changes such as might occur during grinding. They should be ground like carbides, and steps should be taken to prevent localized overheating or sudden heating or cooling of these steels. They are more brittle than conventional high-speed steels and, hence, are not usually suitable for razor-edged tools. In addition, precautions must be taken to protect cobalt high-speed steels from excessive shock and vibration in service.

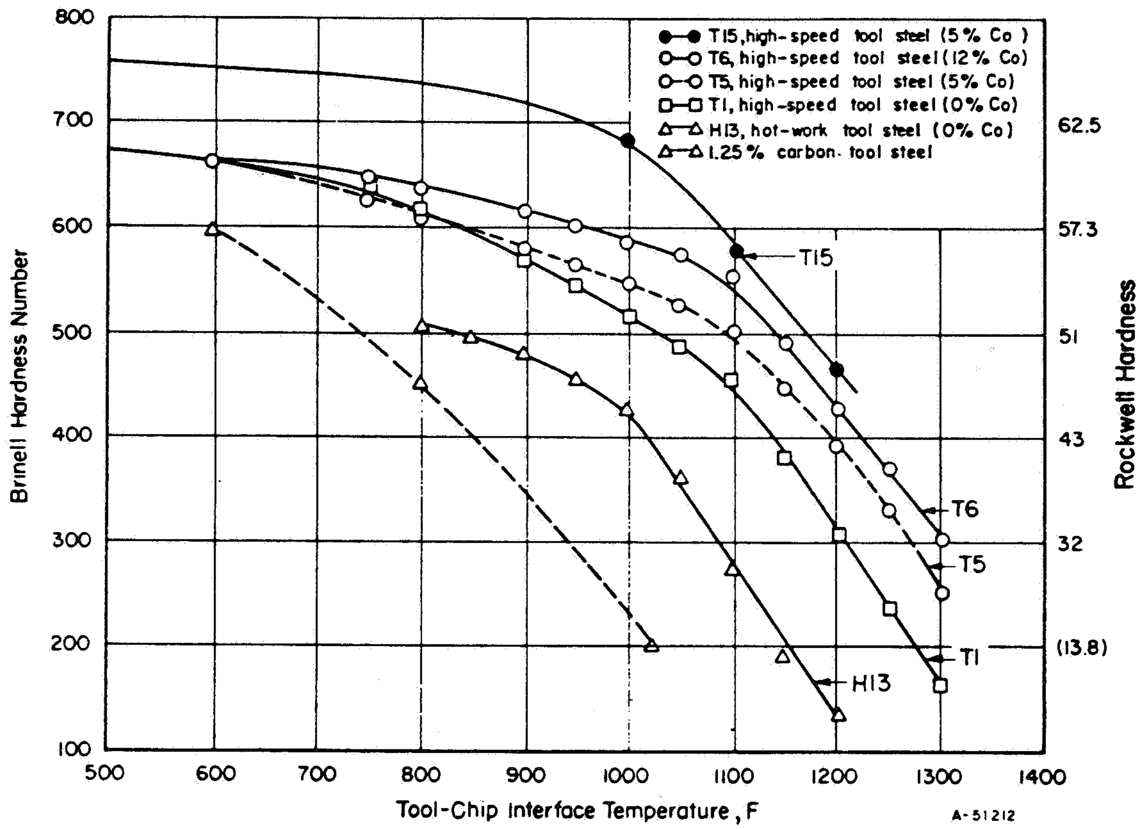


FIGURE 2. EFFECT OF TEMPERATURE ON THE HARDNESS OF VARIOUS TYPES OF TOOL STEEL

While the ultrahards can be hardened to 68-70 R_C, only a relative handful of applications, mostly in turning and continuous cutting operations, have required those hardness levels (Ref. 44). Some of the ultrahigh-hardness high-speed steels perform better in milling cutters while others are better for special drills. The choice depends on details of specific operations. Unless a sound engineering approach is followed, indiscriminate use of any tool material is a sure way to increase tool costs and degrade performance (Ref. 44).

Table VI shows the wide choice of compositions of high-speed steels available to the tool engineer. There is little difference in properties between the conventional molybdenum and tungsten types of high-speed steel. Although each group has its supporters, extensive laboratory and production comparisons of comparable grades of the two types have not consistently established any outstanding

TABLE VI. TOOL-MATERIAL GUIDE FOR HIGH-SPEED STEELS[a]

Group	AISI Code[b]	Composition, weight percent				
		Tungsten	Chromium	Vanadium	Cobalt	Molybdenum
Tungsten	T1	18	4	1	--	--
	T4	18	4	1	5	--
	T5	18.5	4	1.75	8	--
	T6	20	4	2	12	--
	T8	14	4	2	5	--
	T15	14	4	5	5	--
Molybdenum	M1	1.5	4	1	--	8
	M2	6	4	2	--	5
	M10	--	4	2	--	8
	M3	6	4	2.75	--	5
	M3, Type 1	6.25	4	2.50	--	5.70
	M3, Type 2	5.6	4	3.3	--	5.50
	M4	5.50	4	4	--	4.50
	M6	4	4	1.5	12	5
	M7	1.75	3.75	2	--	8.75
	M30	2	4	1.25	5	8
	M33	1.75	3.75	1	8.25	9.25
	M15	6.5	4	5	5	3.5
	M34	2	4	2	8	8
	M35	6	4	2	5	5
	M36	6	4	2	8	5
	M41	6.25	4.25	2	5	3.75
	M42	1.5	3.75	1.15	8	9.5
	M43	1.75	3.75	2	8.25	8.75
	M44	5.25	4.25	2.25	12	6.25

(a) Data from Metals Handbook, Eighth Edition, American Society for Metals (1961), p 672. For commercial listings, reference can be made to "A Guide to Tool Steels and Carbides", Steel (April 21, 1958), Cleveland 13, Ohio; or to "Directory of Tool, Die Steels, and Sintered Carbides", Twenty-Seventh Edition (1959), The Iron Age, Philadelphia 39, Pennsylvania.

(b) When greater-than-average red hardness is needed, cobalt-containing grades are recommended. So-called parallel grades in the molybdenum and tungsten groups are not necessarily comparable. For example, special-purpose steels such as T6, T8, T15, and M6, M35, and M36 seem to have no close counterparts in the opposite group. The unique compositions and properties of these steels often suit them to certain applications without competition.

superiority for either group. Of the conventional high-speed steels shown, recent production figures indicate that the M2 grade constitutes about 40 percent, the M1 grade about 25 percent, the M10 grade about 15 percent, and the T1 grade about 10 percent of the total production. This leaves only about 10 percent for the rest, including the premium grades (Ref. 43).

From the standpoint of cutting ability, gains of 1 or 2 points of hardness in the 65-70 R_C hardness range are much more significant than equivalent differences at lower hardness levels. Thus the ultrahard high-speed steels could become very useful for machining the ultrahigh-strength steels and stainless steel alloys. They also could provide an alternative material for carbides on jobs where cutting speeds are too low for optimum carbide performance, or where carbides fail because of shock or low strength in thin sections (Refs. 44, 45).

Cast-Alloy Tools. As stated earlier in this section, cast cobalt-chromium-tungsten alloys are useful when machining metals at speeds intermediate between carbide and high-speed steel. Different grades are marketed; some are listed in Table VII.

Ceramic Tools. Ceramic cutting tools can be practical and efficient for turning high-strength alloy steels (180,000 to 240,000 psi tensile) (Ref. 46). Ceramic tips seem to transfer more of the heat of cutting to the chips rather than to the work or tool. Consequently, chips do not weld to the tool, and residual stresses in machined surfaces are apt to be much lower than those produced by carbide tools (Ref. 2).

Under the best machining conditions, and for equal tool lives, ceramic tools can cut steels at higher speeds than other commercial tool materials (Ref. 2). Very high speeds are also possible but only when impact shock is negligible, a condition exemplified by light finishing cuts. If no shock or sudden loading occurs at high speeds, ceramic tools can provide long tool lives (Ref. 46).

The low transverse-rupture strengths, poor thermal-shock resistance, and relatively high costs have deterred the widespread use of ceramic tools (Ref. 2). These tools are not as strong as carbide tools, and can break or chip under excessive cutting pressures (Ref. 47). Consequently, ceramic cutting tools cannot be expected to perform adequately on heavy depths of cut, work-hardened or heavily scaled surfaces, and out-of-round work (Ref. 2). If used for heavier

TABLE VII. TOOL-MATERIAL GUIDE FOR CAST ALLOYS

Alloy	Composition, weight percent									Hardness,
	Cobalt	Chromium	Tungsten	Carbon	Nitrogen	Iron	Tantalum	Boron	Others	R_C
Stellite 19[(a)]	50.6	31	10.5	1.9	--	3.0 max	--	--	3.0	55
Stellite 3[(b)]	46.5	30.5	12.5	2.45	3.0 max	3.0 max	--	--	2.0	60
Tantung G[(c)]	46	28	16	2.0	--	2.0	5	0.2	2.0	--
Stellite Star-J[(d)]	40.5	32	17	2.5	2.5 max	3.0 max	--	--	2.5	61
Stellite 98M2[(e)]	37.5	30	18.5	2	3.5	2.5 max	--	--	6	63

(a) Possesses the highest resistance to shock loading or intermittent-cutting effect, but the lowest red hardness of the alloys listed.

(b) Possesses higher hardness, but lower impact strength than Stellite 19. If Stellite 3 can handle the shock conditions of cutting, it is preferable to Stellite 19.

(c) A good compromise of hardness and shock resistance.

(d) Among the materials, the hardness of Star-J is second only to 98M2. It should machine metal faster than Stellites 3 and 19 under moderate impact conditions. Stellite Star-J is suitable for milling cast iron.

(e) Possesses the highest hardness of the materials listed, but only fair impact strength.

depths of cut, ceramic inserts should be thicker than carbide types (Ref. 47). The newer hard-carbide tools are less prone to chipping when used under identical conditions (Ref. 2).

The production superintendent or tool engineer may hesitate to use ceramic tools because they are more costly than carbide tools. However, the higher production output by ceramic tools more than offsets the initial tool costs (Ref. 47). Unfortunately, if chipping causes ceramic tools to wear rapidly, any financial advantage gained by increased metal-removal rate would be lost (Ref. 46).

Ceramic tools' tendency to chip can be minimized by proper tool geometry designed to stress the tool in compression, complete support for the tip by the tool holder, and adequate rigidity of the work-tool setup. Constant positive feeds, good chip control, and a vibration-free turning operation in a lathe possessing adequate horsepower and rigidity are additional requirements (Ref. 2). A lathe also may show a fly-wheel effect from a heavy face plate to help maintain constant speed throughout cutting. The fly-wheel effect is a technique already recognized by tool engineers, particularly in milling operations (Ref. 46).

Tool-holder design is an important factor in the application of oxide tools. The best design is one that will give maximum support to the ceramic tip. In general, four requirements must be met by tool holders:

(1) Substantial cross-sectional area in the shank completely supporting the tip

(2) A seating and clamping design that assures evenly distributed forces on the top of the blank

(3) Adjustable mechanical carbide chip breakers

(4) Tool design that provides minimum deflection.

Standard tool holders using a wedging action to hold the insert against an adjustable chip-curler plate seem to work well. Tool holders made for carbide blanks also can be used for ceramic blanks (Ref. 2).

Much of the unfavorable reputation of ceramic tools results from a failure to take impact shock into account. The transmission of shock, even the smallest amount if rapidly applied, can damage the highly frangible ceramic (Ref. 46).

Although tool failure may still occur more frequently with ceramic tools than with carbide tools, the frequency of failure may be reduced significantly through the use of a shock absorbing, soft shim of aluminum, copper, or brass placed under the insert in the tool holder. These shims should compensate for surface irregularities at the interface of insert and holder. They are sometimes serrated to provide good seating and to increase vibration and shock absorption. The successful application of the serrated copper shim has allowed ceramic machining of high-hardness prototype components (Refs. 2,46).

A tool-alternating technique that prolongs tool life might be of interest here. When machining a preselected number of pieces or a definite linear length, the ceramic tip and holder can be removed from the lathe and set aside. Another holder and tip is placed in the lathe, and the operation is resumed for the same number of pieces or length of cut as the previous tool. By alternating holders and indexing tips, tool life can be increased to a remarkable degree. Ceramic tips that were indexed upon the appearance of wear, but not alternated showed increased tendencies of failure over those alternated. It appears that the variation of clamping pressure caused by prolonged heating is in part responsible for some tool failures (Ref. 46).

Careful sharpening and finishing of oxide cutting tools are also important to the successful use of these tools. Ceramic blanks can be ground with conventional diamond wheels. The grinding techniques are the same as those for carbide tools, except that a tendency toward loading requires a coolant when grinding ceramics. Ceramic materials are notch sensitive, and all grinding marks and scratches on the tool surface should be removed by careful honing with a 350-grit hone and then lapping with 600-grit boron carbide abrasive and oil. Ground surfaces should be examined for possible fractures using a 20-diameter toolmaker's microscope. If no fracture is visible, then the grinding technique employed is probably satisfactory (Ref. 2).

Solid inserts, similar to those made from carbides, are available in ceramic tools. They possess the same advantages of undisturbed machining setups when new cutting positions are selected, providing minimum grinding, and maximum use of ceramic per tool dollar (Ref. 2).

Commercial brands of ceramic cutting tools reported in various machining investigations include:

American Lava 674 (American Lava Corporation)

Carboloy 030 (General Electric Company)

Diamonite (U. S. Ceramic Tile Company)

Sintox (Sintox Corporation of America)

Stupalox (Carborundum Company)

V. R. Ceramic 97 (Vascoloy-Ramet Company).

Cutting Speed. Cutting speed is the most critical variable affecting tool life and metal-removal rates. Tool life decreases exponentially with increases in speed. The relationship between removal rates and speed is linear and direct. Excessive speeds cause high tool-chip interface temperatures and uneconomically short tool lives. Specific recommendations are given in the sections devoted to particular operations.

Feed. All machining operations on these alloys require a positive, uniform feed to prevent glazing, burnishing, or work hardening the surface (Ref. 36). The cutting tool should never dwell or ride in the cut without removing metal (Ref. 7). As an added precaution, all cutters should be retracted when they are returned across the work (Ref. 39).

Acceptable feed rates fall into a narrower bracket than those commonly used on carbon steels. The higher cutting pressures produced by ultrahigh-strength steels and stainless steel alloys require smaller feeds to prevent deflection. On the other hand, excessively light feeds result in continuous cutting in the hardest portion of the work-hardened layer, particularly in the case of austenitic stainless steels (Ref. 29).

Cutting Fluids. The use of cutting fluids is desirable in machining operations on ultrahigh-strength steels and stainless steel alloys. However, the flow should be forceful and continuous. Erratic or interrupted flow on a working cutting edge will do more harm than good, particularly on carbides (Ref. 7).

Highly active cutting fluids are used widely in machining these materials. These fluids promote formation of adsorbed films on freshly cut metal. For example, a sulfur-containing additive reacts with the freshly cut metal to form a metal-sulfide film. This film is more easily sheared than the parent metal and also keeps the chips and tool apart. This protects the tool face from pressure welding. The film, being an excellent lubricant, also reduces chip friction.

Stainless steel alloys respond well to highly active cutting fluids like ordinary sulfurized or sulfochlorinated mineral oil (Ref. 48). As stated above, sulfur imparts improved lubricity and antiweld properties and also provides better chip action by embrittling the metal surface layer on the chip (Ref. 31).

When using high-sulfur oils with carbide tools in high-speed cutting operations, early breakdown of the cutting edges may result from attack on the nickel or cobalt binder because of the high cutting temperatures involved. Flooding the cutting area with fluid will generally cool the tool bit sufficiently to avoid this trouble (Ref. 48). Additions of 10 to 25 percent kerosene is sometimes recommended to minimize this type of attack (Ref. 48).

Water-base coolants are preferred in high-speed operations such as turning, milling, and grinding because of their greater cooling effect. These fluids can be soluble oils or proprietary chemical mixtures. The chemical activity desired is generally provided by chlorine compounds (Ref. 48). A chemical coolant may consist of a synthetic base with added wetting agents, water conditioners, germicides, rust inhibitors, and a nonferrous deactivator. It is diluted 30:1 and is usually flood applied.

Sometimes paste-type lubricants, such as lithopone paste, are used in very low-speed operations such as tapping.

All lubricants must be removed completely from machined parts, particularly if they are to be subjected to high temperatures, either during subsequent fabrication or in service (Ref. 48).

The following tabulation classifies the cutting fluids mentioned and gives the symbols used in subsequent tables of this report.

Symbol	Cutting Fluid
I	Water-base coolant, soluble-oil type, or chemical type
IIa	Sulfurized oil
IIb	Sulfurized oil plus 10 to 25 percent kerosene (or paraffin for tapping)
IIc	Highly sulfurized oil diluted 1:1 with light machine oil
IIIa	Chlorinated oil
IIIb	Highly chlorinated oil
IIIc	Highly chlorinated oil plus inhibited trichlorethane (2:1)
IV	Sulfochlorinated oil
V	Dry

Additional Requirements. One of the important problems facing the production superintendent or tool engineer when machining ultrahigh-strength steel forgings is to decide what areas should be machined at specified hardness levels (Ref. 49). Finish machining of steel in the annealed condition is sometimes recommended because of machining difficulties at the high hardness levels. This recommendation, however, is valid only if the parts are not to warp, and where decarburization is permissible (Ref. 2).

If warpage or decarburization cannot be tolerated, as is the case in aircraft landing gears, some machining should be done in the annealed condition, and most of the remainder in the intermediate heat-treated condition (350 Bhn) (Ref. 2). However, enough machining stock should be left at critical functional and fit-up areas for removal after final heat treatment to 500 Brinell hardness (Ref. 49). A representative process that combines machining and heat treating is shown below:

(1) Rough machine part in the annealed condition

(2) Normalize and then heat treat part to 350 Bhn

(3) Machine part to nearly final dimensions

(4) Reheat treat part to 500 Bhn

(5) Precision machine, or grind the critical area of part to the final dimensions (Ref. 2).

The above process may be applied to medium-alloy steel forgings (AISI H-11). About 5 percent of the metal can be removed in the annealed condition, which is essentially the state in which these forgings come from the supplier. Usually it is only necessary to reduce the various material sections to sizes conducive to proper heat penetration for the subsequent heat-treating operations (Ref. 49).

The intermediate heat treatment is designed to yield hardnesses of 34-38 R_C (320-350 Bhn). Warpage is kept to a minimum by holding the forgings in special fixtures. Between 20 to 85 percent of the metal to be removed is then removed by machining after heat treatment. This means that the entire external contour and some of the internal contours are completed to required finish part dimensions. Following the contour machining, all semifinish milling, some finish milling, all semifinish boring, and some finish boring and drilling operations are performed. Holes are also semifinish tapped at this time. Machining stock of 1/16 to 1/8 inch per surface is left for final finishing where it is required (Ref. 49).

The forging is then given its final heat treatment to bring it up to its maximum hardness level, after which the fully hardened part undergoes its final machining operation. Usually only the functional or fit-up areas such as bolt and shaft holes, and lug and attachment surfaces are machined (Ref. 49).

MILLING-TYPE OPERATIONS

Introduction. This section contains information and data on face milling, end milling, slotting, and slab milling of nonstainless alloy steels, stainless steels, and stainless steel superalloys.

When milling ultrahard alloy steels (510-560 Bhn), only a narrow margin seems to exist between success and failure. The high-strength levels intensify the problems that are easily handled at low-strength levels. In the case of the austenitic stainless alloys, heat, galling, and work hardening contribute to shorter tool life. Galling intensity increases as cutting temperatures rise, while the amount of metal smeared on the cutter edges during milling is proportional to the thickness of the chip as it leaves the cut. The smeared metal and a small part of the underlying edge of the tool later chips off when the tooth reenters the cut. This starts the wearland. Galling and chipping continue to cause gradual wear until the tool fails suddenly (Ref. 39). As the tool wears, the surface finish deteriorates, and it eventually becomes difficult to control dimensions.

Tool wear can be reduced by climb milling, a cutting situation in which the direction of cutter rotation and table movement is the same. This process gives a shorter tool path through the work, and a thinner chip as the tooth leaves the workpiece. Both factors reduce the amount of metal adhering to the cutting edge, and the degree of chipping from that source. Some problems may result from the deflection of thin parts or slender end mills or slotting cutters (Ref. 39), and from the distortion of workpieces accompanying the mechanical relief of residual stresses. In the latter case, thermal-stress-relieving treatments in fixtures prior to machining is desirable.

The machining problems of low tool life and low production rate for these steels are minimized if rigidity of machine, tool, and workpiece, and adequate power to maintain cutting speed exist throughout cutting. The proper selection of feeds, speeds, and depths of cut appropriate to recommended tool materials and designs are equally important (Ref. 50).

Machine-Tool Requirements. Horizontal or vertical knee-and-column milling machines, as well as fixed-bed milling machines, are used on various face- and end-milling operations. Numerically controlled or tracer controlled milling machines can be used for profile and pocket-milling operations. Proper machine design and adequate power are minimum requirements (Ref. 16).

Design. The design and construction of modern machine tools usually provide the rigidity and power needed for milling high-strength and heat-resisting materials. Improved spindle bearings allow greater cutting loads and speeds. The incorporation of a flywheel insures constant cutter speed throughout cutting. Rotating elements are dynamically balanced to eliminate vibration. Other features include wide ranges of feed and speed, ease of operation, and easy accessibility for maintenance. These machines can take full advantage of the latest advances in tooling and machining methods, and the resulting production is significantly greater than with older machines.

Older machines, nevertheless, are being used for milling these materials at lower production rates. Before being used, however, these machines should be strengthened at all vital stress points. All table gibs must be snug and all looseness in the machine and table-feed mechanism eliminated. Lack of play in the spindle and in outboard bearings are additional requirements.

The addition of an appropriate flywheel can sometimes improve the performance of older machines by allowing them to maintain a more constant speed throughout cutting. It is usually installed during a general overhaul to eliminate loose bearings and gears (Ref. 50).

Power Requirements. Adequate power for cutting is absolutely necessary when milling high-strength materials above 350 Brinell hardness. The power required depends on the material and its microstructure. The tooth load (feed in inches per tooth) and the tool angles of the blade or tooth also exert a certain influence. Apparently, very little difference in power consumption results from using different tool materials or cutting fluids (Ref. 50).

Figure 3 is a nomograph, with instructions, that can be used to determine the horsepower requirements of various milling conditions. Conversely, this nomograph also can be used to determine the milling conditions needed to stay within the horsepower rating of a machine contemplated for use (Ref. 51).

Generally speaking, 10 to 15 horsepower is usually sufficient for milling difficult materials. This means, for example, a No. 3 heavy-duty or a No. 4 standard knee-and-column milling machine. However, the machines needed to accommodate large parts may have as much as 25 to 50 horsepower available (Ref. 16).

Types of Milling Operations. Face-milling operations employ the combined action of cutting edges located on both the periphery and face of the cutter. The milled surface is generally at right angles to the cutter axis, and is flat except when milling a shoulder. Face mills and end mills represent the tools used in this operation.

In peripheral or arbor milling the cutting teeth are located on the perimeter of the cutter body. The types of arbor-mounted cutters used include plain mills, helical mills, slab mills, side mills, and slotting cutters.

Face mills produce flat surfaces more efficiently and accurately than plain milling cutters do (Refs. 48, 51, 52). Higher feed rates are also possible with face mills because they are more rugged. In addition, the complicated supports usually required for arbor-mounted cutters are unnecessary when face mills are used. Face milling is done with relative ease and is preferred whenever it is practical, because it minimizes work hardening and chattering.

Milling Cutter Types and Designs. The choice of the milling cutter depends on the type of machining to be done. Face mills, plain milling cutters, and slab mills are usually selected for milling plane surfaces. End mills are suitable for light operations such as profiling and slotting (Ref. 51). Form cutters and gang-milling cutters are used for shaped cuts. Helical cutters are preferred because they promote a smoother cutting action. The use of the smallest diameter cutter with the largest number of teeth without sacrificing necessary chip space minimizes chatter and deflection (Ref. 53). All cutters, however, need adequate body and tooth sections to withstand the cutting loads developed in the particular machining operation.

Cutter Design. Tool angles of a milling cutter should be chosen to facilitate chip flow and immediate ejection of the chip. The controlling angles in this regard are the axial rake, radial rake, and corner angles.

Milling cutters generally use large enough helix angles (axial rake) to provide a good shearing action, and both rake angles are usually made positive to promote this action (Ref. 39).

The axial-radial rake-angle combination should be balanced with the corner angle to produce a positive angle of inclination. Positive inclination angles lift the chip up and away from the machined surface and thus prevent scratching (Ref. 52). Angles of inclination (as well as true rake) can be determined from the intersection of an axial rake/radial rake line with a given corner angle on the nomographs shown in Figure 4. The angles involved are 0-degree axial rake, -10-degree radial rake, and a 30-degree corner angle (Ref. 51).

The use of a corner angle not only encourages positive angles of inclination but it also provides a longer cutting edge to distribute

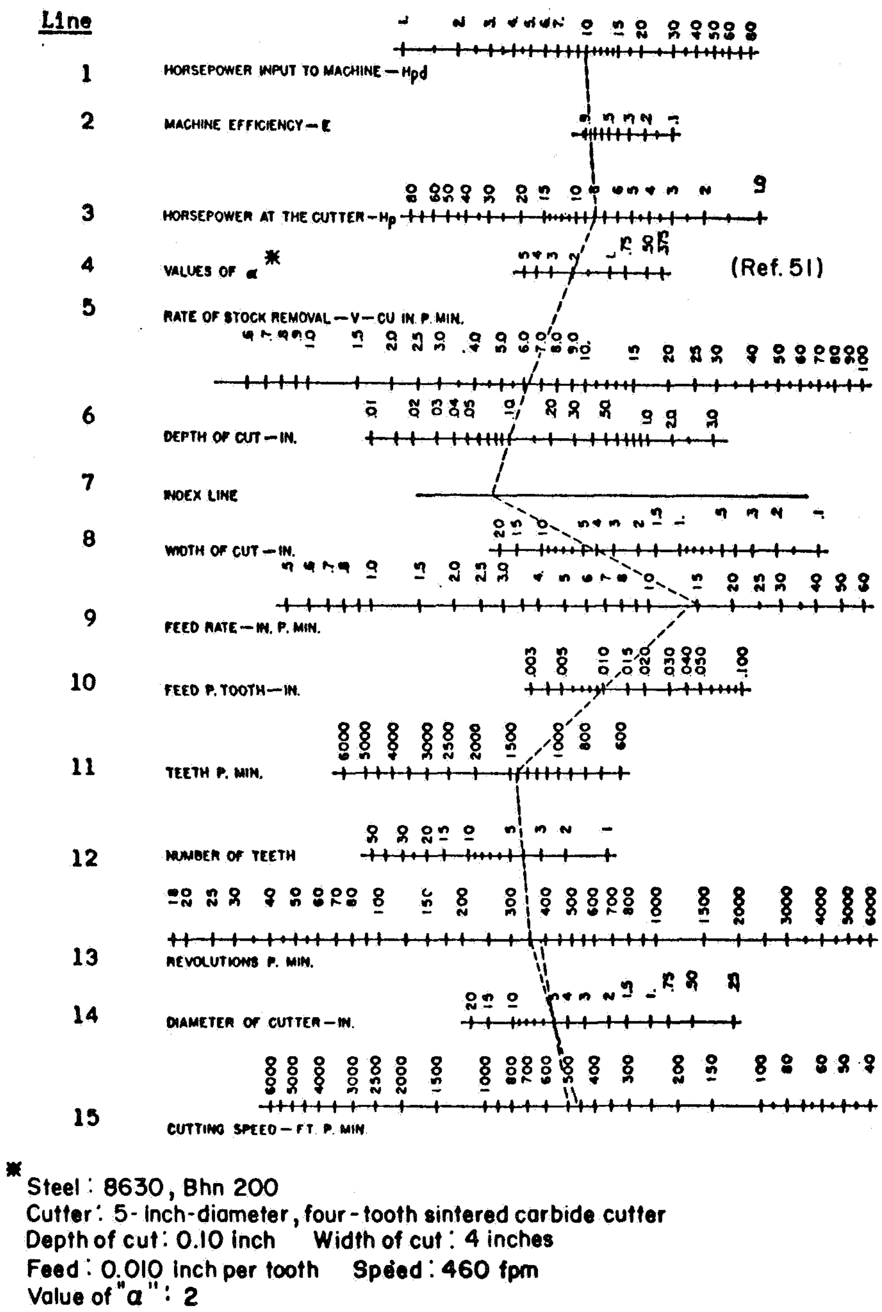


FIGURE 3. NOMOGRAPH FOR DETERMINING HORSEPOWER REQUIREMENTS (REF. 51)

*Steel: 8630, Bhn 200
Cutter: 5-inch-diameter, four-tooth sintered carbide cutter
Depth of cut: 0.10 inch Width of cut: 4 inches
Feed: 0.010 inch per tooth Speed: 460 fpm
Value of "a". 2.

INSTRUCTIONS FOR USING NOMOGRAPH (FIGURE 3) (REF. 51)

Step

1 Locate "cutting speed" on Line 15.
2 Locate "cutter diameter" on Line 14.
3 Draw straight line from Line 15 to Line 13 through the above two points. This locates the rpm value on Line 13.
4 Adjust rpm on Line 13 to nearest value for the machine to be used.
5 Locate on Line 12 the number of "cutter teeth" for the cutter being used.
6 Draw straight line from Line 13 to Line 11 through the points determined on Lines 13 and 12.
7 Locate the desired "feed per tooth" value on Line 10.
8 Draw a straight line from Line 11 to Line 9 through the points determined on Lines 11 and 10.
9 Locate the desired "width of cut" on Line 8.
10 Draw a straight line from Line 9 to the Index Line through the points determined on Lines 9 and 8.
11 Locate the "depth of cut" on Line 6.
12 Draw a straight line from the point determined on the Index Line (Line 7), through the point located on Line 6, to Line 5.
13 See Ref. 51 and locate the value of "a" for the steel being milled on Line 4.
14 Draw a straight line from Line 5 to Line 3 through the points determined on Lines 5 and 4.
15 Locate on Line 2 the efficiency of the machine.
16 Draw a straight line from Line 3 to Line 1 through the points determined on Lines 3 and 2. This determines the power needed to be supplied by the electric motor.

If the power is higher than the rated capacity of the motor, then readjustments in feed rate and cutting speed may have to be made.

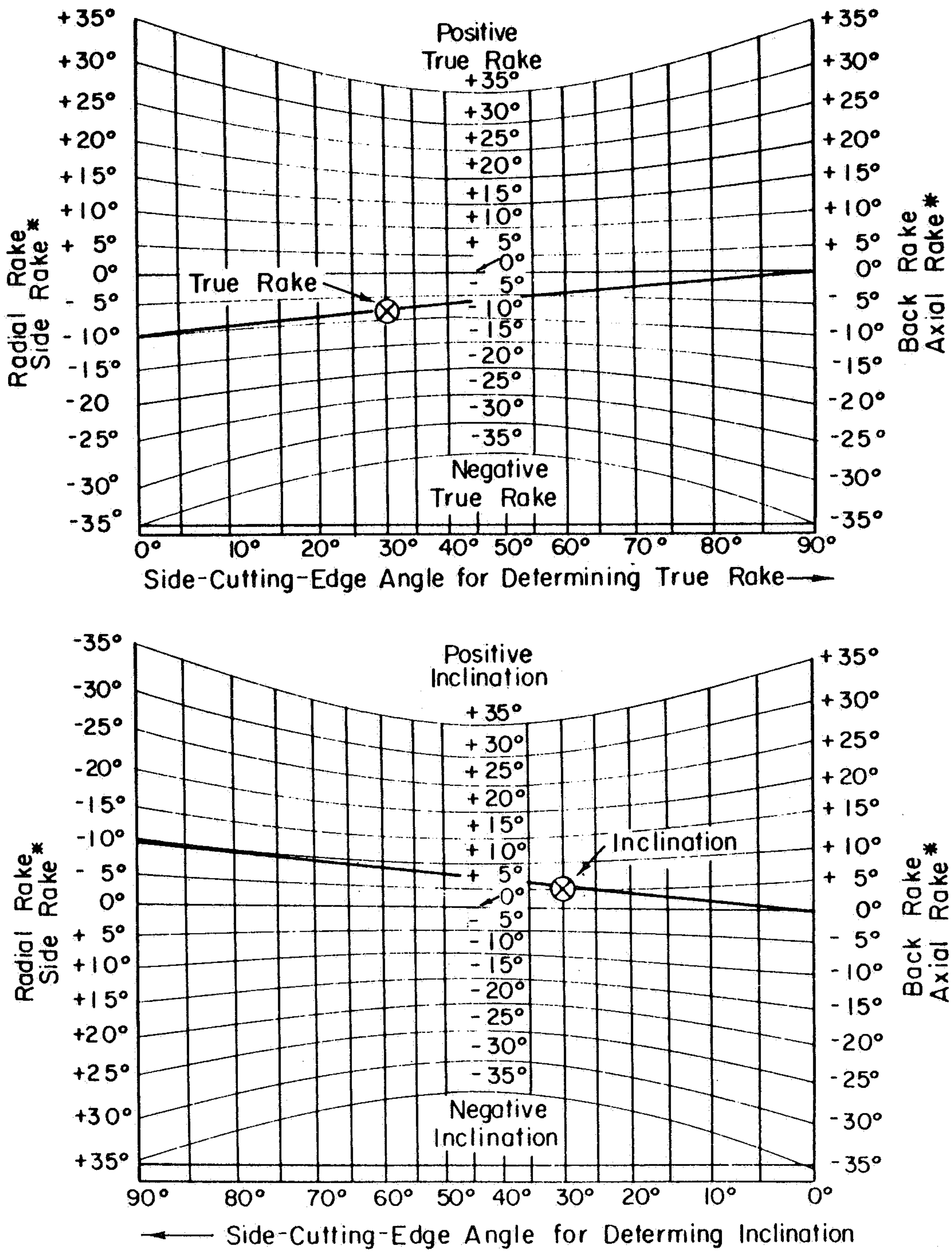


FIGURE 4. NOMOGRAPHS FOR DETERMINING TRUE RAKE AND INCLINATION ANGLES FOR MILLING CUTTERS (REF. 51)

cutting forces over a greater area. This results in lower cutting pressures and temperatures, and less smearing. A 30- to 45-degree chamfer also produces a longer cutting edge and a wider thinner chip. However, a corner angle is usually more effective than a chamfer.

Adequate relief angles are necessary to prevent interference between the surface or land of the tool behind its cutting edge and the milled surface. Sufficient tool wear will eventually eliminate these clearances, and rubbing will occur unless the tool is resharpened. Appropriate secondary clearance angles are sometimes provided, since repeated sharpening will eventually increase the land width until interference finally occurs with the work surface. Relief angles should be compromised between a minimum value for maximum cutting-edge support (minimum edge chipping) and a maximum value for a minimum number of tool grinds. It should be noted, however, that relief angles less than 1-1/2 degrees may lead to excessive smearing along the tool flank, while angles greater than 10 degrees weaken the tool and encourage "digging in" and chipping of the cutting edge. Excessive relief angles also will increase the likelihood of chatter and may present problems in dimensional control (Ref. 50). Relief angles between 5 and 10 degrees are being used for most milling applications.

All cutters should be ground to run absolutely true in order to make the best use of the relatively light feeds used in milling these alloys, and to make certain that all teeth are cutting the same amount of material. The total runout should be less than 0.002 inch and preferably less than 0.001-inch total indicator reading (TIR) (Ref. 50).

Optimum production is obtained through the use of a well-designed and properly ground cutter mounted on an amply powered, rigid milling machine.

Tool Materials. The choice of the proper tool material is not a simple matter and depends on the various factors already described on page 14.

High-speed steels, cast alloys, and carbides are being used for milling high-strength materials. Specific information and data on these tool materials, including the types and grades that are commercially available, are given on pages 15, 18, and 20.

Among the high-speed steel tools used, the cobalt grades seem to give the best results. The T5 and T15 grades are used for maximum tool life (Ref. 31), whereas the regular T1, M1, M2, M3, and M10 grades are suitable for low-production milling. The M3, Type 2 steels seem to be well suited for inserted-blade shell mills. Tantung G, the cast-alloy tool material, seems to provide better tool life than the T15 high-speed steel.

Among the carbides, the C-6 grade gives the best tool life for the martensitic-type steels. The C-1 and C-2 carbides show rapid wear, while the C-7 grade tends to chip at the cutting edge. Carbide C-2, however, seems to give the best tool life when milling Vascojet 1000 at 500 Bhn, as well as when milling the austenitic-type stainless steels and superalloys. Carbide cutters should not be used, however, if the machine tool is not in good condition or if a setup cannot be made rigid enough.

High-speed steel cutters are usually more reliable than carbide cutters and are popular because of their ready availability (Refs. 16, 29,53,54). High-speed steel, furthermore, can be used under conditions of insufficient rigidity, as well as for slots and formed cuts.

Some differences in the performance of high-speed steel cutters, however, may exist between cutters of the same type and geometry supplied by different manufacturers. This difference can be attributed to the geometry, composition, and/or heat treatment of the tool. Hence, purchasing specifications should cover both the grade and the heat treatment of the steel.

Setup Conditions. Fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture (rather than the clamps) should absorb the cutting forces (Ref. 40). Fixtures should be rugged enough to minimize distortion and vibration.

The selection of speeds, feeds, and depth of cut in any setup should take into account the rigidity of the setup, the optimum metal-removal rate/tool-life values, and the surface finish and tolerances needed on the finished part.

Cutting Speed. Cutting speed is the most critical factor in milling high-strength materials. Excessive speeds will cause overheating of the cutting edges and subsequent rapid tool failure (Ref. 50). Consequently, when starting a new job, it is advisable to select a depth of cut for the job and then start in the lower portion of speed ranges suggested in pertinent tables of data. Sufficient flywheel-assisted spindle power should be available to prevent loss in cutting speed as the cutter takes the cutting load (Ref. 40).

Feed. Feed rates for milling high-strength alloys should be limited to avoid overloading the cutters, fixtures, and milling machine. Lighter feeds reduce the tool/chip contact area, thereby reducing the incidence of welding and premature chipping. Delicate types of cutters and flimsy workpieces also require lighter feeds to avoid deflection. However, too light a feed may produce a rubbing rather than a cutting action, thereby inducing a serious work-hardened layer on the part (Ref. 38). Hence, if deflection is a problem, it is better to reduce the depth of cut rather than lowering the feed below 0.002 inch per tooth (ipt).

It is also important to maintain a uniform, positive feed since cutters must not idle or stop in the cut (Ref. 38). Positive gear feeds without backlash are preferred to hydraulic feeds (Ref. 50). Climb milling is preferred to up milling for carbide tools because rubbing is avoided at the beginning of the cut (Refs. 29,31,53). Also, the downward motion assists rigidity and diminishes the tendency to chatter. The disadvantage of climb milling is the necessity for positive control of backlash in the table drive.

Depth of Cut. The selection of cut depth depends on setup rigidity, part rigidity, the dimensions and tolerances required, and the type of milling operation undertaken. Depths of cut up to 0.25 inch can be used if sufficient power is available. When scale is present, the nose of each tooth must be kept below the hard skin to avoid rapid tool wear.

Cutting Fluids. Sulfurized mineral oils and highly chlorinated oils are used extensively and are usually flood applied (Refs. 29,54). Water-base fluids are also used.

Good tool life can be obtained by using the spray-mist technique for all water-base coolants. The mist should be applied ahead of a peripheral milling cutter (climb cutting), and at both the entrance and exit of a face-milling-type cutter. Pressurizing the fluid in an aspirator system permits better penetration to the tool-chip area, better cooling, and better chip removal (Ref. 38).

There are a number of proprietary fluids that are producing excellent results.

Additional Requirements. All milling operations require reasonably close supervision. The supervisor should check new milling setups before operations begin. Thereafter, he should spot check for nicks and scratches to prevent potentially defective parts from being processed too far.

Milling cutters should be kept sharp (Ref. 39). Hence, they should be examined for "buildup" and early indications of dulling. Some people advocate that the cutting faces should be honed between cuts to remove buildup so that the cutter teeth will not be damaged. Others recommend having at least two cutters available in case replacement is necessary for a given operation. Minimum downtime usually occurs when the entire cutter is replaced by a new one. In any case cutters should be removed before too much wear develops.

The normal criterion of wear for replacing a cutter is considered to be a wearland of 0.015 inch for a carbide cutter and 0.060 inch for a high-speed steel cutter (Ref. 16).

Cutters should be carefully ground and lapped (preferably liquid honed) to exact dimensions before use. These tools usually have an average life of three times that of equivalent tools used in the as-received condition. Additional costs for this extra care in preparing cutters are more than made up in reduced cost per inch of cut as a result of reducing downtime, tripling cutter life, and producing higher quality work (Ref. 38).

Careful handling and meticulous inspection of high-hardness steel parts are also required throughout processing. Because of their adverse effect on fatigue life, no nicks, scratches, stamped indentations, or scribed lines should be permitted to remain on the finished machined part. The average surface roughness after machining should not exceed 125 microinches. Average surface-roughness values of 63 or even 32 microinches will permit better fatigue life (Ref. 50).

Face-Milling Operations. Face mills are used for milling relatively wide, flat surfaces usually wider than 5 inches (Ref. 51). Typical designs include those of "Futurmill", "Ingersoll", and other makes. Special face mills are also used and include the rotating insert and conical types.

Diameters of face mills are important. They should be as wide as but not appreciably wider than the width of the cut. If a smaller diameter cutter can perform a given operation and still overhang the cut by 10 percent, then a larger cutter should not be used. Conversely, it is not good practice to bury the cutter in the work (Ref. 51).

Face mills and shell-end mills range from 1 to 6 inches in diameter. Face mills are also available in diameters larger than 6 inches. Good surface finish and freedom from distortion are desirable when machining a wide surface. Surface finish, in the case of milling improves significantly with decreasing feed, but only slightly with increasing speed.

Table VIII contains typical data on feeds, speeds, depths of cut, and tool designs. Figures 5 and 6 explain the tool-angle nomenclature and the tool designs used on carbide and high-speed steels, respectively.

End-Milling Operations. End milling, a type of face-milling operation, utilizes the cutting action of teeth on the circumferential surface and one end of a solid-type cutter (Ref. 51). End-milling cutters are used for facing, profiling, and end-milling operations and include the standard end mills and two-lip end or slotting mills (Ref. 51). Chip crowding, chip disposal, and tool deflection are possible problems in some end-milling operations. Another problem is the production of nonperpendicular sides or grooves. Sometimes the high cutting pressure needed to machine strong alloys causes cutter deflection. The problem is minimized by using a four-flute end mill and then taking cuts in proportion to the rigidity of the cutter.

End-Mill Requirements. Due to their inherent lack of rigidity, end mills should be as short as practical (Ref. 39), and their shank diameter should equal their cutting diameters. The proper combinations of hand of helix and hand of cut should be considered to avoid deflection of the cutter in the direction of an increasing depth of cut (Ref. 51).

When milling slots where the end of the cutter is in contact with the work, the hand of the helix and the hand of the cut should be the same. This means a right-hand helix for a right-hand cut, or a left-hand helix for a left-hand cut (Refs. 48,51).

TABLE VIII. FACE MILLING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS WITH HELICAL FACE MILLS[a]

Alloy			Carbide[b]					High-Speed Steel[c]				
Group	Group Representative	Alloy Condition[d]	Tool Grade[e]	Tool Design[f]	Depth of Cut, inch	Feed[g], ipt	Cutting Speed[h], fpm	Tool Grade[e]	Tool Design[f]	Depth of Cut, inch	Feed[g], ipt	Cutting Speed[h], fpm
						Nonstainless Alloy Steels						
	Cr-Mo low-alloy steels											
A1	A-4130	Ann	C-6	A, C	0.25	0.012	425	T1, M1	L, N	0.25	0.005-0.015	60-120
		(230 Bhn)	C-7	A, C	0.05	0.014	500	T1, M1	L, N	0.05	0.006-0.012	80-150
E1		HT	C-6	B, C	0.25	0.006	250	T5, M3	M, N	0.25	0.005	55
		(350 Bhn)	C-7	B, C	0.05	0.007	375	T5, M3	M, N	0.05	0.006	75
			--	B, C	0.10	0.005	450	T15	M, N	0.10	0.010	80
	Cr-Ni-Mo low-alloy steels											
C1	A-4340	Ann	C-6	A, C	0.25	0.012	425	T1, M1	L, N	0.25	0.010	120
		(230 Bhn)	C-7	A, C	0.05	0.014	500	T1, M1	L, N	0.05	0.012	150
F1	A-4340	HT	C-6	B, C	0.25	0.006	250	T5, M3	M, N	0.25	0.005	55
		(350 Bhn)	--	--	--	--	--	T1	M, N	0.062	0.010	65
			--	--	--	--	--	T5, M3	M, N	0.05	0.006	75
			C-7	B, C	0.05-0.10	0.005-0.007	300-350	T15	M, N	0.10	0.010	80
F1	A-4340	HT	C-6	B, C	0.25	0.005	175	T15	N	0.25	0.003	35
		(410 Bhn)	--	--	--	--	--	T1	N	0.062	0.010	25-40
			C-7	B, C	0.05-0.10	0.005-0.006	200-250	T15	N	0.05	0.004	75
G1	A-4340	HT	--	--	--	--	--	--	--	--	--	--
		(515 Bhn)	C-6	D	0.10	0.005	90-180	T15	N	0.062	0.010	8-10
	5 Cr-Mo V die steels											
D2	H-11	Ann, wrought	C-6	A, C	0.25	0.012	375	T1, M1	L, N	0.25	0.010	90
			C-7	A, C	0.05	0.014	475	T1, M1	L, N	0.05	0.012	135
		Ann, cast	C-6	A, C	0.15	0.007	300	--	--	--	--	--
			C-7	A, C	0.05	0.004	370	--	--	--	--	--
F2	H-11	HT	C-6	B, C	0.25	0.006	225	T5, M3	L, N	0.25	0.005	55
		wrought	C-7	A, C	0.05	0.007	275	T5, M3	L, N	0.062	0.010	60
		(350 Bhn)	--	--	--	--	--	--	--	0.05	0.006-0.008	75
		Cast	C-6	B, C	0.10	0.004	120	--	--	--	--	--
		(444 Bhn)	C-6	B, C	0.13	0.003	150	--	--	--	--	--
G2	H-11	HT, wrought	C-2	E	0.25	0.003	90	T15	N	0.25	0.001	20
		(515-560 Bhn)	C-2	E	0.05	0.004-0.008	125	T15	N	0.05	0.002	25
	Maraging steels											
G1	18 Ni Co Mo	HT	C-2	F	--	0.001-0.002	150	--	--	--	--	--
		(52 R_C)	C-2	--	0.060	0.0035	140-170	--	--	--	--	--
G2	Cr-Ni-Mo steels											
	D6a	HT	C-2	G	0.060	0.008-0.010	65	--	--	--	--	--
		(56-58 R_C)	--	--	--	--	--	--	--	--	--	--
						Stainless Steel Alloys						
	Straight-chromium grades											
B4	Type 405	Ann	C-6	H	0.250	0.008	375	T1, M1	O, P, R	0.250	0.005	60-120
		(150-200 Bhn)	--	--	--	--	--	--	--	--	0.008-0.015	60-80
			C-7	H	0.050	0.010	445	T1, M1	O, P, R	0.050	0.003-0.006	140-160
B5	Type 410	Ann	C-6	H	0.250	0.008	440	T1, M1	O, P, R	0.250	0.005	60-110
		(160-220 Bhn)	--	--	--	--	--	T1, M1	O, P, R	--	0.008-0.015	60-80
			C-7	H	0.050	0.010	500	T1, M1	O, P, R	0.050	0.003-0.006	140-160
F5	Type 410	HT	C-6	H	0.250	0.005	220	T5, M3	S	0.250	0.004	55
		(300-350 Bhn)	C-7	H	0.050	0.006	260	T5, M3	S	0.050-0.060	0.005-0.010	75-100
	Type 410	HT	C-6	J	0.10	0.010	250	--	S	0.060	0.005	70
		(415 Bhn)	C-2	--	0.10	0.007	175	--	--	--	--	--
D5	Type 440B	Ann	C-6	H	0.250	0.008	400	T1, M1	O, P, R	0.250	0.005	50-75
		(215-260 Bhn)	C-7	H	0.050	0.010	450	T1, M1	O, P, R	0.050	0.003-0.006	80-90
G5	Type 440B	HT	C-6	J	0.250	0.004	120	T15	S	0.250	0.003	35
		(375-440 Bhn)	C-7	J	0.050	0.005	160	T15	S	0.050	0.004	55
	Precipitation-hardenable grades											
D6	17-7PH	Ann	C-2	H	0.250	0.008	375	T1, M1	O, P, R	0.250	0.005	65-80
		(160-180 Bhn)	C-2	--	0.10	0.005-0.010	100-145	T15	O, P, R	0.060	0.005-0.015	50-115
			C-2	H	0.050	0.010	470	T1, M1	O, P, R	0.050	0.003-0.006	70-120
F6	17-7PH	HT	C-2	H	0.250	0.004	220	T5, M3	S	0.250	0.003-0.0035	40
		(380 Bhn)	C-2	H	0.050	0.005	250	T5, M3	S	0.050	0.004	55
	17-7PH	HT	--	--	--	--	--	--	--	--	--	--
		(444 Bhn)	C-2	J	0.10	0.002-0.005	125-160	--	S	--	--	--

TABLE VIII. (Continued)

Group	Group Representative	Alloy Condition(d)	Carbide(b) Tool Grade(e)	Carbide(b) Tool Design(f)	Carbide(b) Depth of Cut, inch	Carbide(b) Feed(g), ipt	Carbide(b) Cutting Speed(h), fpm	High-Speed Steel(c) Tool Grade(e)	High-Speed Steel(c) Tool Design(f)	High-Speed Steel(c) Depth of Cut, inch	High-Speed Steel(c) Feed(g), ipt	High-Speed Steel(c) Cutting Speed(h), fpm
D7	Chromium-nickel grades Type 347	Ann (160-220 Bhn)	C-2	H	0.25	0.008	300	T1, M1	O, P, R	0.250	0.005	60-85
			C-3	H	0.050	0.010	375	T1, M1	O, P, R	0.050	0.003-0.006	60-110
					Austenitic Stainless Steel Superalloys							
D8	Nonheat treatable 19-9 DL		C-2	H	0.10	0.015	110	T15	O, P, R	0.06	0.015	50
		ST	C-2	H	0.25	0.004	120	T15	O, P, R	0.25	0.013	55
		(200 Bhn)	C-3	H	0.05	0.006	180	T15	O, P, R	0.05	0.005	65
E8	Timken 16-25-6	ST	C-5a, C-6	H	0.125-0.250	0.006-0.010	50-75	--	--	--	--	--
			C-7a, C-7	H	0.03-0.125	0.003-0.006	50-100	--	--	--		
	Age-hardenable		--	--	--	--	--	T15	O, P, R	--	0.004	60
D9	Discaloy	ST	--	K	--	0.002	120	--	--	--	--	--
		HT	C-1	H	0.10	0.015	150	T6	O, P, R	--	--	40
E9	A-286	ST	C-1	H	0.125-0.250	0.006-0.010	50-75	T15	O, P, R	0.06	0.015	50
		(190 Bhn)	C-2	H	0.03-0.125	0.003-0.006	50-100	T15	O, P, R	0.25	0.003	55
			C-2	H	0.25	0.004	120	T15	O, P, R	0.05	0.005	65
			C-3	H	0.05	0.006	180	T15	--	--	--	--
		STA	--	--	0.10	0.010	100	M2	S	--	--	30
E9		(321 Bhn)	--	K	--	0.002	120	--	--	--	--	--
			C-2	K	0.25	0.004	120	T15	S	0.25	0.003	55
			C-3	K	0.05	0.006	190	T15	S	0.05	0.005	75

(a) From References 1, 15, 16, 38, 40, 53-63.

(b) Cutting fluids for carbide tools.

Alloy	Cutting Fluid
Nonstainless alloy steels	I, V (dry)
Stainless steel alloys	I, V (dry)
Stainless steel superalloys (austenitic only)	I, IIa, IIIa, IV, V (dry)

(c) Cutting fluids for high-speed steel tools:

Alloy	Cutting Fluid
Nonstainless alloy steels	I, IIa
Stainless steel alloys	I
Stainless steel superalloys (austenitic only)	I, IIa

See page 25 for specific types.

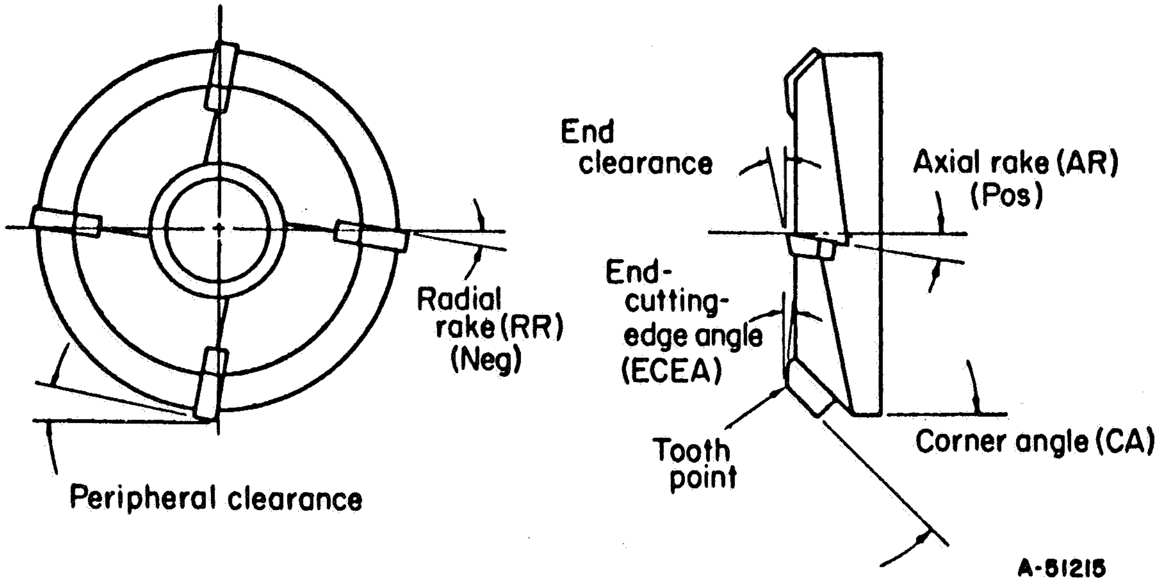
(d) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.

(e) CISC designation for carbides (see page 15); AISI designations for high-speed steels (see page 18).

(f) See Figures 5 and 6 for tool angles involved.

(g) For AISI 4340 steel of 350 Brinell hardness, a feed of 0.005 to 0.006 ipt seems best since heavier feeds, around 0.01 ipt, will cause chipping of carbide cutting points. Rapid wear seems to occur at feeds less than 0.005 ipt (Ref. 50).

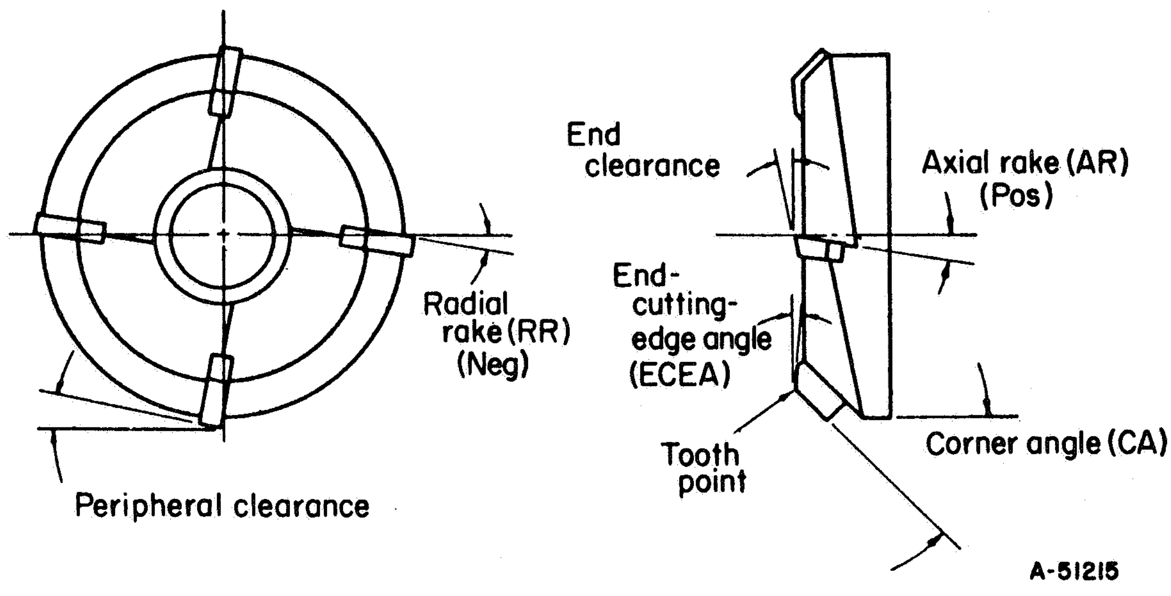
(h) For AISI 4340 steel of 350 Brinell hardness, a speed of 350 fpm represents the maximum speed for good tool life. Better tool life is obtained at lower speeds. At hardnesses around 515 Brinell, 4340 steel can be milled with fairly good tool life up to 180 fpm. Tool life drops abruptly for small increases in speed above 180 fpm (Ref. 50).



	Tool-Geometry Code									
	A	B	C	D(a)	E(a)	F	G	H	J	K
Tool angles, degrees										
Axial rake	0 to -10	-5 to -15	0	0	-15	-7	0	0 to 5	0	-4
Radial rake	0 to -10	-5 to -15	-7	-15	-15	-7	-15	0 to 5	0	-11
End relief	5 to 7	5 to 7	6	8 to 10	8	6	10	5 to 7	10	10
Peripheral relief	3 to 5	3 to 5	6	8 to 10	8	6	10	6 to 10	10	10
End-cutting edge	5 to 10	4 to 7	5 to 6	5	5	5	6	4 to 6	5	5
Corner	45	45	45	45	45	60	45	45	45	45
Nose radius, inch	--	--	--	1/16	1/16	--	--	--	--	--

(a) For steels around 500 Bhn, relief anlges near 10 degrees give longer tool life than do standard relief angles (5 to 6 degrees). Relief angles near 8 degrees are more practical for multiple-tooth cutters.

FIGURE 5. TOOL-GEOMETRY DATA FOR CARBIDE FACE MILLS



	Tool-Geometry Code						
	L	M	N	O	P	R	S
Tool angles, degrees							
Axial rake	10 to 12	5 to 10	0	0 to 5	5 to 10	10 to 20	0
Radial rake	10 to 12	5 to 10	0	0 to 5	5 to 10	10 to 20	0
End relief	5 to 7	5 to 7	6	5 to 7	5 to 10	5	8
Peripheral relief	3 to 5	3 to 5	6	6 to 10	3 to 5	5	8
End-cutting edge	5 to 10	4 to 10	5	4 to 6	--	--	5
Corner	45	45	30	45	--	--	30
Nose radius, inch	--	--	0.02	--	--	--	--

FIGURE 6. TOOL-GEOMETRY DATA FOR HIGH-SPEED STEEL FACE MILLS

When profile milling, where the periphery of the cutter is doing the cutting, the opposite is true, i.e., left-hand helix for a right-hand cut and vice versa (Refs. 48,51).

Cutter diameter for both profile or pocket milling depends on the radius needed on the pockets. Helical-style cutters give better performance than the straight-tooth designs do. The shank of end mills should be somewhat softer than the cutter flutes to avoid breakage between shank and flutes.

An axial hole should be part of the high-speed steel-cutter design to allow coolant injection at the site of cutting (Ref. 50).

Tool Materials for End Mills. Either high-speed steel or carbide cutters can be used for end-milling operations, depending on the hardness of the material.

Workpiece hardness is a critical variable insofar as end milling with high-speed steels is concerned. Good tool life can be obtained only up to a work hardness of 480 Bhn. Beyond this hardness value, tool life decreases rapidly. Some investigators believe that, for practical purposes, high-strength steels with hardnesses of 500 Bhn and above are virtually unmachinable with high-speed steel end mills. High-speed steels suggested for best results include T15, M34, M10, M4, M7, and M3, Type 2.

Carbide end mills are recommended for steels harder than 500 Bhn. It is important that the milling machine used is suitable for carbide milling. Carbide Grade C-2 seems to give better tool life than the C-6 grade, which tends to fail prematurely by chipping (Ref. 50).

Tables IX and X provide machining data for profile milling and slotting operations. Figures 7 and 8 illustrate the designs used on tools for these operations.

Slab-Milling Operations. Slab milling is used to improve the tolerances and surface finish on extrusions. The operation is usually done on a heavy-duty, fixed-bed mill such as the Sundstrand Rigid Mill.

Rigid setups are necessary. Arbor-mounted cutters require arbors of the largest possible diameter. In addition, the arbor should be supported on both sides of the cutter with overarm

TABLE IX. PROFILING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS WITH HELICAL END MILLS[a]

Alloy			Carbide[b]						High-Speed Steel[c]					
			Tool			Cutting	Feed[h], ipt		Tool			Cutting	Feed[h], ipt	
Group	Group Representative	Alloy Condition[d]	Grade[e]	Design[f]	Depth of Cut, inch	Speed[g], fpm	3/4-In. Diam	1-1/4-In. Diam	Grade[e]	Design[f]	Depth of Cut, inch	Speed[g], fpm	3/4-In. Diam	1-1/4-In. Diam
						Nonstainless Alloy Steels								
	Cr-Mo low-alloy steels													
A1	A-4130	Ann	C-2	--	0.05	375	0.004	0.007	M1, M10	B	0.05	110	0.003	0.004
		(150-230 Bhn)	C-2	--	0.015	475	0.005	0.006	M1, M10	B	0.015	135	0.004	0.005
E1	A-4130	HT	C-2	A	0.05	225	0.002	0.0025	M3, M10	B	0.05	50	0.0015	0.002
		(350 Bhn)	C-2	A	0.015	300	0.003	0.0035	M3, M10	B	0.015	65	0.002	0.003
	Cr-Ni-Mo low-alloy steels													
C1	A-4340	Ann	C-2	--	0.05	375	0.004	0.007	M1, M10	B	0.05	110	0.003	0.004
		(230 Bhn)	C-2	--	0.015	475	0.005	0.006	M1, M10	B	0.015	135	0.004	0.005
F1	A-4340(j)	HT	C-2	A	0.05	225	0.002	0.0025	M3, M10	B	0.05	50	0.0015	0.002
		(350 Bhn)	C-2	A	0.015	300	0.003	0.0035	M3, M10	B	0.015	65	0.002	0.003
									T15	C	0.25	55	0.002	
G1	A-4340(k)	HT	C-2	A	0.25	50-100		0.0015	T15	B	0.05	20	0.001	0.001
		(510 to	C-2	A	0.05	100	0.0015	0.0007	T15	B	0.015	30	0.0015	0.0015
		560 Bhn)	C-2	A	0.015	150	0.002	0.001	T15	C	0.25	55	0.001	
	5Cr-Mo-V die steels													
D2	H-11	Ann	C-2	--	0.05	375	0.004	0.006	M1, M10	B	0.05	90	0.0015	0.004
		(160-220 Bhn)	C-2	--	0.015	425	0.0045	0.007	M1, M10	B	0.015	130	0.002	0.004
F2	H-11(j)	HT	C-2	A	0.05	200	0.0015	0.0025	M3, M7	B	0.05	50	0.001	0.0015
		(350 Bhn)	C-2	A	0.015	275	0.0025	0.0035	M3, M7	B	0.015	70	0.0015	0.002
G2	H-11(k)	HT	C-2	A	0.10-0.25	60-80	--	0.0015	--					
		(515-560 Bhn)	C-2	A	0.05	75	0.0005	0.0007	T15	B	0.05	20	0.0003	0.0005
			C-2	A	0.015	120	0.0007	0.001	T15	B	0.015	30	0.0005	0.0007
	Maraging steels		Machines as well as annealed 4130 or 4340 steels shown above											
D3	18Ni-Co-Mo	Ann												
		HT	--	--	--	--	--	--	T15, M2	D	0.25	42	0.0005-0.001	
		(52 R_C)												
E1	Cr-Ni-Mo steel													
		Ann	--	--	--	--	--	--	M33, T15	B	--	55	--	0.006
G1	D6	HT												
		(52 R_C)	--	--	--	--	--	--	M33, T15	B	--	24	--	0.003
						Stainless Steel Alloys								
	Straight-chromium grades													
B4	405	Ann	C-2	--	0.050	325	0.002	0.004	M1, M10	E, F	0.050	95	0.001	0.002
		(150-200 Bhn)	C-2	--	0.015	375	0.003	0.005	M1, M10	E, F	0.015	125	0.002	0.003
B5	410	Ann	C-2	--	0.050	375	0.002	0.004	M1, M10	E, F	0.050	100	0.001	0.002
		(160-220 Bhn)	C-2	--	0.015	425	0.003	0.005	M1, M10	E, F	0.015	125	0.002	0.003
		HT	C-2	A	0.050	185	0.001	0.003	M3, M7	G	0.050	55	0.0005	0.001
F5	410	(300-350 Bhn)	C-2	A	0.015	250	0.002	0.004	M3, M7	G	0.015	70	0.001	0.002
		HT	C-2	A	0.25	90		0.001	T15	G	0.25	55	0.002	0.003
		(415 Bhn)												

TABLE IX. (Continued)

Alloy Group	Alloy Group Representative	Alloy Condition(d)	Carbide(b) Tool Grade(e)	Carbide(b) Tool Design(f)	Carbide(b) Depth of Cut, inch	Carbide(b) Cutting Speed(g), fpm	Carbide(b) Feed(h), ipt 3/4-In. Diam	Carbide(b) Feed(h), ipt 1-1/4-In. Diam	High-Speed Steel(c) Tool Grade(e)	High-Speed Steel(c) Tool Design(f)	High-Speed Steel(c) Depth of Cut, inch	High-Speed Steel(c) Cutting Speed(g), fpm	High-Speed Steel(c) Feed(h), ipt 3/4-In. Diam	High-Speed Steel(c) Feed(h), ipt 1-1/4-In. Diam
					Stainless Steel Alloys (Continued)									
(Straight-chromium grades) (Continued)														
D5	440 B	Ann	C-2	--	0.050	325	0.002	0.004	M1, M10	E, F	0.050	65	0.001	0.002
		(215-260 Bhn)	C-2	--	0.015	375	0.003	0.005	M1, M10	E, F	0.015	90	0.002	0.003
G5	440 B	HT	C-2	A	0.050	185	0.001	0.003	M3, M7	G	0.050	55	0.0005	0.001
		(300-350 Bhn)	C-2	A	0.015	250	0.002	0.004	M3, M7	G	0.015	70	0.001	0.002
Precipitation-hardenable grades														
D6	17-7 PH	Ann	C-2	--	0.050	350	0.002	0.004	M1, M7	F	0.050	75	0.001	0.002
		(160-180 Bhn)	C-2	--	0.015	400	0.003	0.005	M1, M7	F	0.015	100	0.002	0.003
F6	17-7 PH	HT	C-2	--	0.050	180	0.0005	0.001	M3, M7	F, G	0.050	35	0.0002	0.0007
		(380-440 Bhn)	C-2	--	0.015	220	0.001	0.002	M3, M7	F, G	0.015	50	0.0005	0.001
									T15	F, G	0.25	70	0.002	--
Chromium-nickel grades														
D7	347	Ann	C-2	--	0.050	275	0.002	0.004	M1, M10	E, F	0.050	75	0.001	0.002
		(160-220 Bhn)	C-2	--	0.015	325	0.003	0.005	M1, M10	E, F	0.010	100	0.002	0.003
					Austenitic Stainless Steel Superalloys									
Nonheat-treatable grades														
D8	19-9 DL	ST	C-2	--	0.050	100	--	0.003	T15	H	0.050	40	--	0.003
		(200 Bhn)	C-2	--	0.015	150	0.003	0.004	T15	H	0.010	50	0.002	0.005
E8	Timken 16-25-6	ST	C-2	--	0.050	110	--	0.003	T15	H	0.050	45	--	0.002
		280	C-2	--	0.015	160	0.003	0.004	T15	H	0.010	60	0.002	0.003
Age-hardenable grades														
D9	Discaloy		--	--	--	--	--	--	--	--	--	--	--	--
E9	A-286	ST	C-2	--	0.050	100	--	0.003	T15	H	0.050	40	--	0.003
		(180-220 Bhn)	C-2	--	0.015	150	0.003	0.004	T15	H	0.010	50	0.002	0.005
		STA	C-2	--	0.050	110	--	0.003	T15	G	0.050	45	--	0.002
			C-2	--	0.015	160	0.003	0.004	T15	G	0.010	60	0.002	0.003
									T15	G	0.25	40		0.002

Footnotes appear on the following page.

Footnotes for Table IX.

(a) From References 1, 15, 16, 32, 38, 49, 50, 53-56, 60-64.

(b) Cutting fluids for carbide tools are:

Alloy	Cutting Fluid
Nonstainless alloy steels	I, V
Maraging steels	IIIb
Stainless steel alloys	I, IIa, V
Stainless steel superalloys	IIa, IIIa, IV

(c) Cutting fluids for high-speed steel tools are:

Alloy	Cutting Fluid
Nonstainless alloy steels	I, IIa
Stainless steel alloys	I
Stainless steel superalloys	IIa, IIb, IIIa, IV .

Soluble-oil (20:1) or chemical-emulsion (40:1) types of coolants (I) have been used successfully in the ratios indicated. They are applied as a mist through a 3/16-inch axial hole in the cutter using 50- to 75-psi air pressure. Chips that otherwise would clog the cutting site and damage the cutter should be blown away (Ref. 50).

See page 25 for specific types.

(d) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.

(e) CISC designations for carbides (see page 15); AISI designations for high-speed steels (see page 18).

(f) See Figure 8 for tool angles involved.

(g) The cutting speeds shown are nominal. They usually can be adjusted to somewhat higher or lower values except where noted to the contrary.

(h) Feeds are for 3/4 and 1-1/4-inch diameter end mills. Lower feeds are needed for 1/8-inch end mills, and somewhat higher values are possible for 2-inch end mills (Ref. 50).

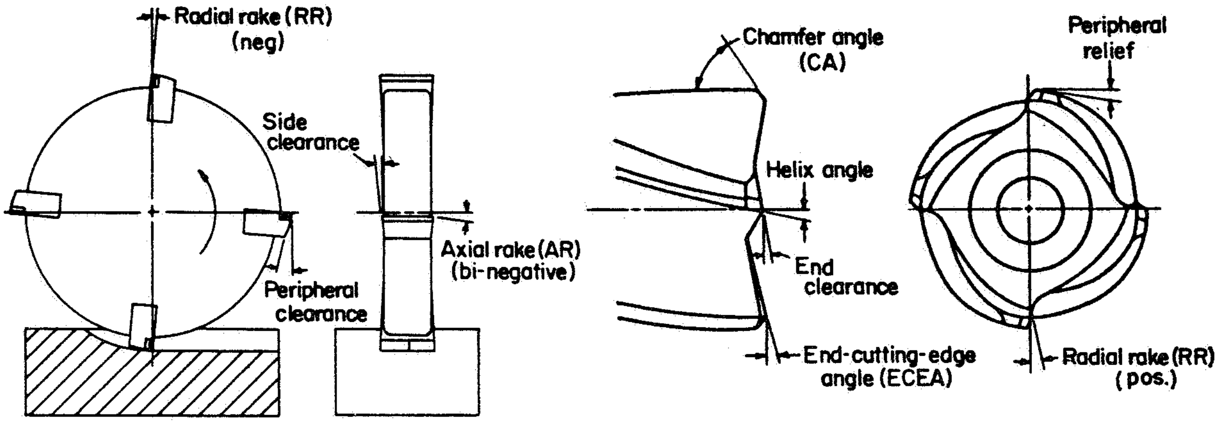
(i) For AISI 4340 and H-11 steels of 350 Brinell hardness, good tool life is possible at 0.001 to 0.003-ipt feed, 55-fpm speed, and 1/4-inch depth of cut when T15 high-speed steel cutters are used. Some investigators believe that steel harder than 500 Bhn is virtually unmachinable with high-speed steels (Ref. 50).

(j) For AISI 4340 and H-11 steels of 515 to 560 Brinell hardness, reasonable tool life can be expected at 0.001 to 0.002-ipt feed, 50 to 100-fpm cutting speed, and 1/4-inch depth of cut. At lower speeds, severe chatter can occur, which would decrease tool life rapidly. Tool life also decreases at speeds greater than 50 fpm, decreasing rapidly up to 80 fpm, and then less rapidly at somewhat higher speeds (Ref. 50).

TABLE X. SLOTTING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS WITH PERIPHERAL AND END MILLS[a]

			Carbide Peripheral Mills[b]					Carbide or High-Speed-Steel End Mills[c]					
	Alloy	Alloy	Tool		Depth of Cut[g],	Cutting Speed[h],	Feed[j],	Tool		Depth of Cut[g],	Cutting Speed[h],	Feed[j], ipt	
Group	Group Representative	Condition[d]	Grade[e]	Design[f]	inch	fpm	ipt	Grade[e]	Design[f]	inch	fpm	3/8-In. Diam	3/4-In. Diam
							Nonstainless Alloy Steels						
C1	Cr-Ni-Mo low-alloy steels A-4340	Ann (210-217 Bhn)	--	--	--	--	--	M-2 high-speed steel	E	--	125-150	--	0.002
		HT (350, Bhn)	C-2	A	--	200-210	0.001-0.003	Ditto	E	--	55	--	0.002
G1		HT 510 Bhn	C-2	A	0.250	150-200	0.005	--	--	--	--	--	--
D2	5Cr-Mo-V die steels H-11	HT (510-560 Bhn)	C-2	A	0.250	200-300	0.005	--	--	--	--	--	--
E1	Cr-Ni-Mo steel D6a	HT (56 R_C)	C-2	B	0.125	230	0.003	Carbide C-2	F	0.125	40	--	0.003 (1-1/4-in. diam)
		HT (58 R_C)	C-2	B	0.125	125	0.002	--	--	--	--	--	--
							Stainless Steel Alloys						
B5	Straight-chromium grades Type 410	HT (45 R_C)	C-2	C	0.25	200	0.005	--	--	--	--	--	--
D6	Precipitation-hardenable grades 17-7PH AM-350	HT (444 Bhn)	C-2	C	0.25	125	0.003	--	--	--	--	--	--
							Stainless Steel Superalloys						
E9	Austenitic age-hardenable grades A-286	STA (320 Bhn)	C-2	D	0.25	150	0.005	--	--	--	--	--	--

(a) From References 16, 50, 54, 59.
(b) All materials are usually cut dry when carbide slotting cutters are used.
(c) Soluble-oil coolants (1:20) can be used for both high-speed steel and carbide end mills.
(d) Ann = annealed; HT = heat treated; STA = solution treated and aged.
(e) CISC designations for carbides (see page 15); AISI designations for high-speed steels (see page 18).
(f) See Figure 7 for the tool angles involved. The bi-negative type of grind for the slotting cutters involves a 5- or a 10-degree axial rake ground from the center of the tooth face to each side of the tooth, and produces an angular tool face (Ref. 50).
(g) Depths of cut greater than 1/4 inch result in a rapid decrease in tool life (Ref. 50).
(h) The speed ranges shown should give good tool life (Ref. 50).
(j) Maximum tool life occurs around 0.008 ipt, unless severe machine vibrations are encountered. Down milling (climb milling) is preferred since chip welding and tooth chippage may occur at all feeds when up milling (Ref. 50).



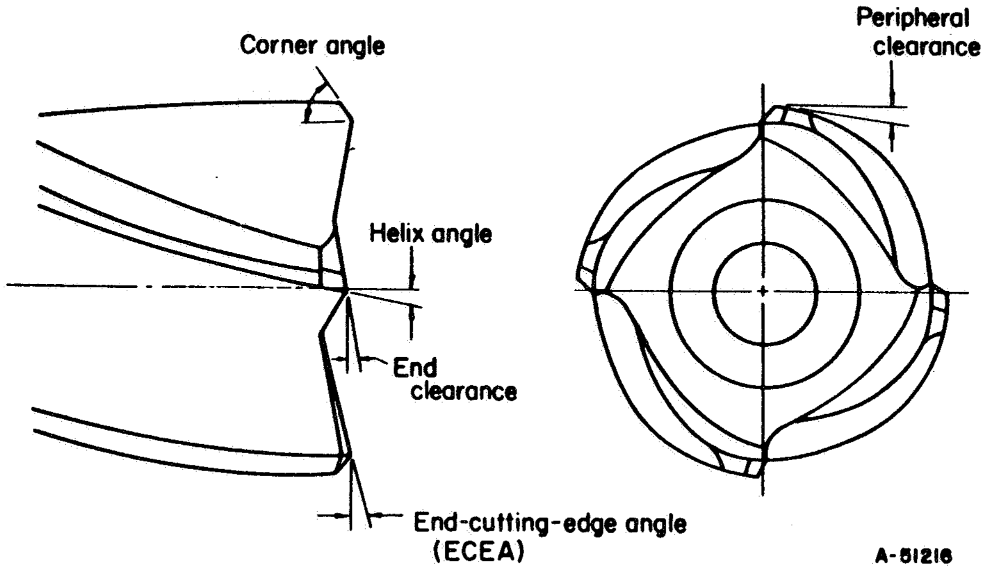
a. Slotting Cutter

b. End Mill

	Tool-Geometry Code					
	Carbide Slotting Cutter				End Mill	
	A	B	C	D	E	F
Tool angles, degrees						
Axial rake[a]	-5	-5	-5	-10	HSS[b]	Carbide
Helix	NA[c]	NA	NA	NA	30	0
Radial rake	-10	0	-5	0	10	0
End clearance	--	--	--	--	--	--
Peripheral clearance	8	10	8	8	7	15
End-cutting edge	1	1	1	1	--	--
Corner	45 x 0.030	45 x 0.030	45 x 0.030	45 x 0.030	45 x 0.060	45 x 0.030
Nose radius, inch	--	--	--	--	--	--

(a) Bi-negative.
(b) HSS – high-speed steel.
(c) NA – not applicable.

FIGURE 7. TOOL-GEOMETRY FOR SLOTTING CUTTERS AND MILLS



	Tool-Geometry Code							
	A	B	C	D	E	F	G	H
Tool angles, degrees								
Helix	(Carbide) 0	30	35 RH	30	30	25	35 RH	20
Radial rake	0[a]	7	15	10	10 to 20	7	--	5
End clearance	--	2	6	--	--	2	--	1
Peripheral clearance	15	5	6	7	5 to 10	6	15	4
End-cutting edge	3	3	--	--	--	3	--	3
Corner	45 x 0.030	--	45 x 0.060	45 x 0.060	--	--	45 x 0.060	--
Nose radius, inch	--	--	0.07	--	--	--	--	--

(a) A 0-degree radial rake seems to show minimum chatter at low cutting speeds. Severe chatter and low tool life are likely at radial rakes angles of either +5 or -5 degrees.

FIGURE 8. TOOL-GEOMETRY DATA FOR END MILLS

supports. The arbor should have just the proper length required for the number of cutters mounted and the arbor support employed (Ref. 51). Arbor overhang beyond the outer support should be avoided since it is conducive to chatter and vibration (Ref. 51).

Cutters should be mounted as close to the column face of the milling machine as the work will permit. The cutters of opposite hand to the cut should be used so that the cutting forces will be absorbed by the spindle of the machine (Ref. 51). This is accomplished by using cutters with a left-hand helix for a right-hand cut, and vice versa. The effective force involved will press the cutter and arbor against the spindle, holding them in position, thus providing a more rigid setup. When two milling cutters are used end to end on the arbor, both right-hand and left-hand helices should be used. This setup neutralizes the cutting forces that tend to push the cutters away from the work (Refs. 48,51).

Carbide cutters are preferred for spar milling because of the higher production rates attainable. Helical-style cutters are recommended since they provide wider and thinner chips than do the corresponding straight-tooth types.

Table XI gives machining data used for slab milling the nonstainless alloy steels and the various grades of stainless steels.

TURNING AND BORING

Introduction. Turning, facing, and boring operations are essentially similar and constitute one of the lesser machining-problem areas for the nonstainless alloy steels and stainless steels. They give less trouble than milling, especially when cutting is continuous rather than intermittent. The speeds used for turning can be used for boring and facing cuts. However, the depths of cut and feeds usually have to be reduced for boring because of an inherent lack of rigidity of the operation.

Machine-Tool Requirements. In addition to the machine-tool requirements described earlier (page 12), it is very important that the proper cutting-speed ranges for these materials are available on the machine. In general, the range of spindle speeds available on many of the existing lathes is not wide enough to cover the lower speeds needed for some of the heat-treated steels.

TABLE XI. SLAB MILLING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS WITH PLAIN HELICAL MILLS (REF. 63)

			Carbide(a)					High-Speed Steel(b)				
	Alloy		Tool					Tool				
Group	Group Representative	Alloy Condition(c)	Grade(d)	Design(e)	Depth of Cut, inch	Feed, ipt	Cutting Speed, fpm	Grade(d)	Design(e)	Depth of Cut, inch	Feed, ipt	Cutting Speed, fpm
					Nonstainless Alloy Steels							
	Cr-Mo low-alloy steels											
A1	A-4130	Ann	C-6	A, C	0.25	0.009	375	T1, M1	L, N	0.25	0.008	105
		(150-230 Bhn)	C-7	A, C	0.05	0.011	475	T1, M1	L, N	0.05	0.010	140
E1	A-4130	HT	C-6	B, C	0.25	0.006	225	T15	M, N	0.25	0.004	50
		(350 Bhn)	C-7	B, C	0.05	0.008	275	T15	M, N	0.05	0.006	65
	Cr-Ni-Mo low-alloy steels											
C1	A-4340	Ann	C-6	A, C	0.25	0.009	375	T1, M1	L, N	0.25	0.008	105
		(150-230 Bhn)	C-7	A, C	0.05	0.011	475	T1, M1	L, N	0.05	0.010	140
F1	A-4340	HT	C-6	B, C	0.25	0.006	225	T15	M, N	0.25	0.004	50
		(350 Bhn)	C-7	B, C	0.05	0.008	275	T15	M, N	0.05	0.006	65
G1	A-4340	HT	C-6	D	0.25	0.004	80	T15	N	0.25	0.001	15
		(510-560 Bhn)	C-7	--	0.05	0.006	100	T15	N	0.05	0.002	20
	5Cr-Mo-V die steels											
D2	H-11	Ann	C-6	A, C	0.25	0.009	350	T1, M1	L, N	0.25	0.008	85
		(160-220 Bhn)	C-7	A, C	0.05	0.011	440	T1, M1	L, N	0.05	0.010	120
F2	H-11	HT	C-6	B, C	0.25	0.006	200	T5, M3,	L, N	0.25	0.004	50
		(350 Bhn)						M1		0.10	0.004	35
			C-7	A, C	0.05	0.008	275	T5, M3	L, N	0.05	0.006	65
G2	H-11	HT	C-6	E	0.25	0.003	80	T15	N	0.25	0.001	20
		(515-560 Bhn)	C-7	E	0.05	0.004	110	T15	N	0.05	0.002	25
					Stainless Steel Alloys							
	Straight-chromium grades											
B4	Type 405	Ann	C-6	H	0.25	0.006	350	T1, M1	O, P, R	0.25	0.003	100
		(150-200 Bhn)	C-7	H	0.05	0.008	400	T1, M1	O, P, R	0.05	0.005	130
B5	Type 410	Ann	C-6	H	0.25	0.006	400	T1, M1	O, P, R	0.25	0.003	100
		(160-200 Bhn)	C-7	H	0.05	0.008	460	T1, M1	O, P, R	0.05	0.005	130
F5	Type 410	HT	C-6	H	0.25	0.005	200	T5, M3	S	0.25	0.002	50
		(300-350 Bhn)	C-7	H	0.05	0.007	240	T5, M3	S	0.05	0.003	65
D5	Type 440 B	Ann	C-6	H	0.25	0.006	350	T1, M1	O, P, R	0.25	0.003	65
		(215-260 Bhn)	C-7	H	0.05	0.008	400	T1, M1	O, P, R	0.05	0.005	85
G5	Type 440B	HT	C-6	J	0.25	0.004	100	T15	S	0.25	0.001	35
		(375-440 Bhn)	C-7	J	0.05	0.005	145	T15	S	0.05	0.002	70
	Precipitation-hardenable grades											
D6	17-7 PH	Ann	C-6	H	0.25	0.006	350	T1, M1	O, P, R	0.25	0.005	75
		(160-180 Bhn)	C-7	H	0.05	0.008	430	T1, M1	O, P, R	0.05	0.007	105
F6	17-7 PH	HT	C-6	H	0.25	0.005	190	T15	S	0.25	0.004	35
		(380-440 Bhn)	C-7	J	0.05	0.007	225	T15	S	0.05	0.003	50
	Chromium-nickel grades											
D7	Type 347	Ann	C-2	H	0.25	0.006	290	T1, M1	O, P, R	0.25	0.003	70
		(160-220 Bhn)	C-3	H	0.05	0.008	350	T1, M1	O, P, R	0.05	0.005	105

TABLE XI. (Continued)

Group	Alloy Group Representative	Alloy Condition(a)	Carbide(a) Tool Grade(d)	Carbide Tool Design(e)	Carbide Depth of Cut, inch	Carbide Feed, ipt	Carbide Cutting Speed, fpm	High-Speed Steel Tool Grade(d)	High-Speed Steel Tool Design(e)	High-Speed Steel Depth of Cut, inch	High-Speed Steel Feed, ipt	High-Speed Steel Cutting Speed, fpm
					Austenitic Stainless Steel Super Alloys							
D8	Nonheat-treatable grades 19-9DL	ST (180-220 Bhn)	C-2	H	0.25	0.006	140	T5, M15	O, P,	0.25	0.005	50
			C-3	H	0.05	0.008	200	T5, M15	O, P, R	0.05	0.008	70
E8	Timken 16-25-6	ST (280 Bhn)	C-2	H	0.25	0.006	110	T15	O, P, R	0.25	0.005	50
			C-3	H	0.05	0.008	165	T15	O, P, R	0.05	0.008	65
E9	Age-hardenable grades A-286	ST (180-220 Bhn)	C-2	H	0.25	0.006	140	T5, M15	O, P, R	0.25	0.005	50
			C-3	H	0.05	0.008	200	T5, M15	O, P, R	0.05	0.008	70
		STA (280-320 Bhn)	C-2	K	0.25	0.006	110	T15	S	0.25	0.005	50
			C-3	K	0.05	0.008	165	T15	S	0.05	0.008	65

(a) Cutting fluids for carbide tools are:

Alloy	Cutting Fluid
Nonstainless alloy steels	I, V
Stainless steel alloys	I, V
Stainless steel superalloys (austenitic only)	IIa, IIIa, IV

(b) Cutting fluids for high-speed steel tools are:

Alloy	Cutting Fluid
Nonstainless alloy steels	I
Stainless steel alloys	I
Stainless steel superalloys (austenitic only)	IIa, IIIa, IV

See page 25 for specific types.

(c) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.

(d) CISC designations for carbides (see page 15); AISI designations for high-speed steels (see page 18).

(e) See Figures 5 and 6, showing face-milling geometry, for the tool angles involved.

Lathes should have either a variable-speed drive for the spindle, or the spindle gear train should have a geometric progression of 1.2 or less in order to provide speed steps of 20 percent or less for more precise speed selections (Ref. 16).

The trend in new lathes is toward variable-speed drives. Rigidity, dimensional accuracy, rapid indexing of tools, and flexibility are additional features that are being emphasized (Ref. 16).

The application of numerically controlled machines for turning is spreading rapidly. On lathes equipped with tracer or numerical control, variable-speed and feed features are being added so that the speed and feed can be optimized during contouring operations (Ref. 16).

Lathes with 10-horsepower ratings should be suitable for most turning operations. Workpieces ranging between 1 and 10 inches in diameter can be turned on a standard or heavy-duty 1610 engine lathe.* These lathes have a range of spindle speeds that almost meet the requirements previously described (Ref. 16). Figure 9 is a chart that can be used for determining motor horsepower of lathes (Ref. 63).

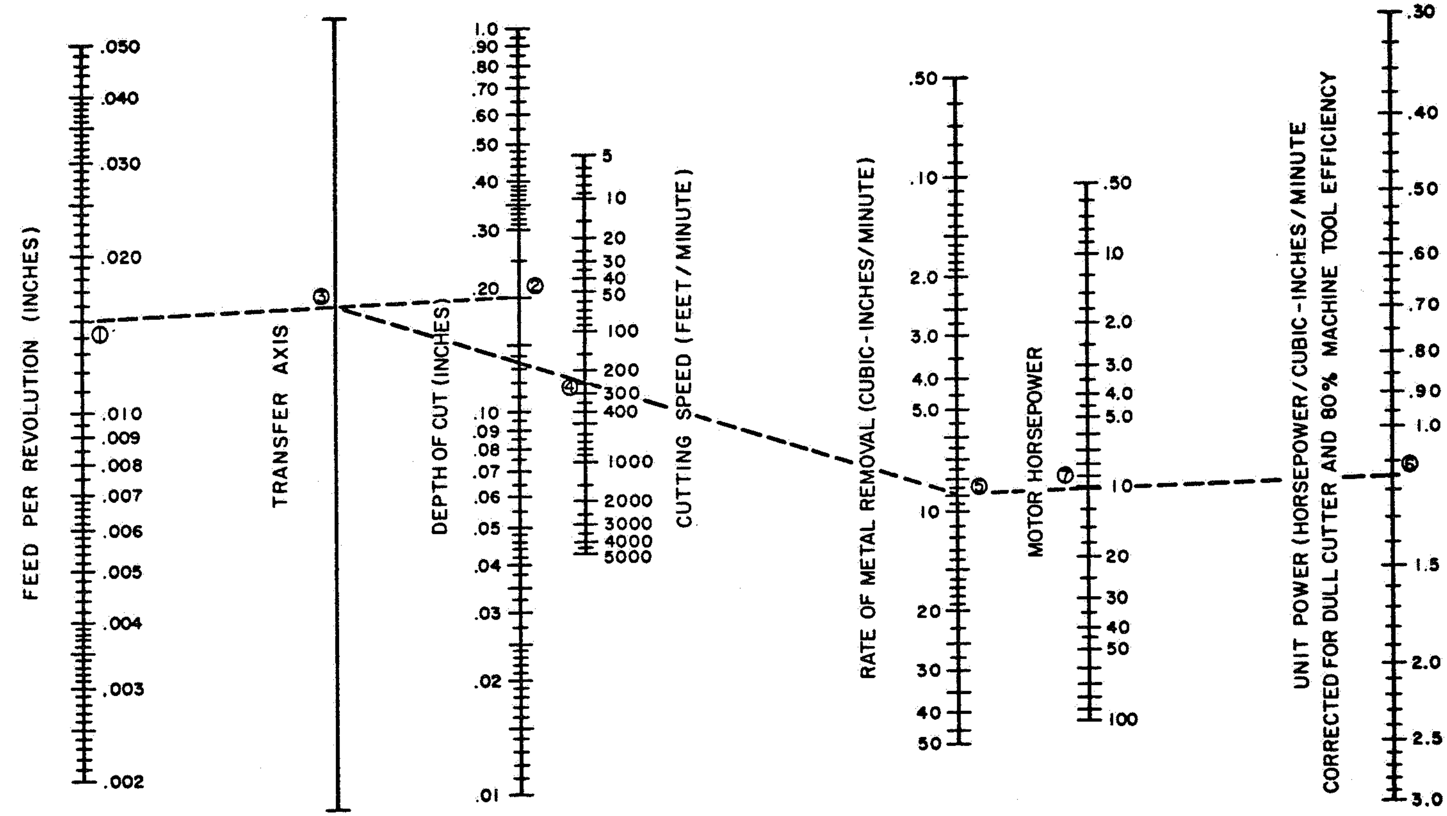
A modern lathe in good condition should be used since it provides production rates of five to ten times the rates possible with older machines. Vibration and lack of rigidity are common problems in older equipment.

Cutting Tools. Standard cutting tools are used for turning these high-strength materials and are available in a variety of shapes, sizes, tool angles, and tool materials. High-speed steel, carbide, and cast-alloy tools can be used. In all cases, a minimum of overhang is needed to avoid tool deflection.

Tool Angles. Cutting tools should be designed to provide proper chip flow, minimum tool wear and tool forces, and maximum heat dissipation. The factors contributing to these desirable qualities include the rake, side-cutting edge, and relief angles, as well as the nose radii (Ref. 64).

Positive-, zero-, and negative-rake angles can be used depending on the properties of the workpiece, the tool material, and

*1610 is the lathe industry designation on 16-inch swing over bed and 10-inch swing over cross slide.



HORSEPOWER =12 × DRILL DIAMETER × SPEED × FEED × UNIT POWER

Cutting Conditions:

Feed: .015 ipr

Depth of cut: .200 in

Speed: 250 fpm

Unit Power: 1.15 hp/in^3/min

To Determine Motor Horsepower:

Connect feed ① with depth of cut ② to obtain point ③ on transfer axis. Connect ③ with cutting speed ④ to obtain point ⑤ on rate of metal removal scale. Connect point ⑤ with unit power ⑥ to obtain 10.4 horsepower at motor, point ⑦.

FIGURE 9. ALIGNMENT CHART FOR DETERMINING MOTOR HORSE POWER IN TURNING (REF. 63)

the type of machining operation. Positive rakes are used to reduce cutting forces, and to produce better surface finishes (Refs. 16,28, 30,63,65). Although positive-rake tools cut more freely than negative-rake tools their cutting edges are weaker. Consequently, negative-rake tools are more effective in roughing cuts or other applications where the additional edge strength is needed. In the case of ceramic tools, double negative rakes are usually advisable since they take advantage of the high compressive strengths of ceramic-tool materials.

The side-cutting-edge angle is the next important angle to the cutting tool. A large angle lowers the cutting temperature by increasing the tool-chip contact area available for heat dissipation and by reducing cutting pressures. A side-cutting-edge angle of 20 degrees or possibly larger is sometimes recommended for turning operations that do not require form tools or machining against a shoulder (Refs. 7,28,30,31). The larger side-cutting-edge angles and their longer cutting edges reduce cutting temperatures and pressures. These reductions often permit greater feeds and speeds for equivalent tool life. Furthermore, thin chips are produced, and the depth-of-cut notch is reduced or eliminated. Excessive angles, however, can cause chatter (Ref. 28). The side-cutting-edge angle for ceramic tools is usually set at about 15 degrees. It should be increased to 30 to 45 degrees when machining surface scale or out-of-round pieces. When the latter is done, the speed should be reduced to eliminate possible chatter due to increased chip width.

The side and end relief angles of a cutting tool provide clearance between the tool flank and the work, and the values selected usually represent a compromise between two extremes. Insufficient relief will cause tool rubbing against the workpiece as soon as a little tool wear has occurred. Excessive relief weakens the support of the cutting edge. The same situation applies to the end-cutting-edge angle. This angle supports the nose of the cutting tool by resisting the forces of tool feed. Relief angles between 5 and 15 degrees can be used depending on the tool material, but these angles should have values no greater than those just sufficient to prevent drag between the tool and workpiece (Refs. 31,48).

The long, tough, stringy chip obtained when turning stainless steel-type alloys is difficult to remove from the lathe and to keep clear of the work. Hence, the use of a chip breaker is recommended for good chip control, particularly on all boring and finishing cuts (Ref. 48). The most usable chip breaker for ceramic tools is the adjustable clamped chip-breaker plate, which also forms a broad clamp on the tool tip. Chip-breaker adjustment is important. The chip must curl above the holder to break away properly. Otherwise, the chip forms a loose coil that may become entangled with the face of the tool undermining its tip.

Finally, the nose radius of the tool must be considered. This element of tool geometry joins the side and end cutting edges of the tool. The scalloped effect produced by a tool with a nose radius provides better surface finishes, shallower scratches, and a stronger workpiece than the notched effect produced by a sharp-pointed tool. Oversized radii, however, interfere with cutting action, causing tool vibrations that tend to work harden the machined surface and reduce tool life (Refs. 28,30,65,66). A small nose radius, usually considered to be less than one-half the depth of cut, reduces work hardening and chatter, and generates less heat. However, tool life is somewhat lower due to the reduced strength of a small radius. A nose radius one-half of the depth of cut, or somewhat larger, thins the chip that, in turn, tends to increase tool life. It also presents a much stronger cutting edge. When turning alloy steels and stainless steel alloys, use the smallest nose radius that proves serviceable. For general usage, a 1/32-inch nose radius should be satisfactory (Ref. 28). In the case of ceramic tools, the nose radius should be larger than the depth of cut if this is practical, but not so large as to induce chatter and vibrations (Ref. 2).

Tool Preparation. To minimize work hardening, cutting tools should be carefully ground and finished before use (Ref. 66). The direction of finishing scratches on the chip-bearing surfaces should correspond to the intended direction of chip flow. A rough surface can cause a properly designed tool to deteriorate rapidly.

The life of a carbide tool also can be extended if the sharp cutting edge is slightly relieved by honing, especially, tools used in heavy roughing cuts. Since all tools must be sharp, only a slight hone is recommended to give the added strength to the cutting edge and to reduce chipping. Tools for light, precision boring require either no honing or only a very slight removal of the feather edge. On finish cuts, where feeds of 0.003 inch per revolution (ipr) might be required, it is desirable to lap the cutting edge rather than hone it (Refs. 7,28,30). A negative edge land has been used to reduce the chipping of ceramics. This land should slope 25 degrees to the cutting direction and produce dead sharp edges. The width of this land should be 3/32 to 1/8 inch for a 3/8-inch-round insert.

Tool Materials. High-speed steel, cast-alloy, and cemented carbide cutting tools are suitable for lathe-turning tools. In this operation carbide tools can be used to advantage. Cobalt grades of high-speed steels seem to perform best in boring operations (Ref. 66). Ceramic tools can be used on nonstainless alloy steels hardened to around 510-560 Bhn. The selection of a tool material for a given job depends on the factors described in the section on milling.

As shown by experience, high-speed steel cutters are most suitable for form cuts, heavy plunge cuts, and interrupted cutting. Nonferrous cast-alloy tools can be used for severe plunge cuts, machining to dead center, and cutting narrow grooves. Carbide cutting tools are recommended for continuous cuts, high-production items, extensive metal-removal operations, and scale removal. Carbide cutting tools are sensitive to chipping and, hence, require "overpowered", vibration-free lathes as well as more rigid tool-work setups. If these conditions cannot be met, then high-speed steels must be used.

Ceramic tools work best on long uninterrupted cuts. Cutting speed seems to have less effect on ceramic tools than it usually has on other tool materials. Rates of cutting at the start of a cut, however, can influence tool life, depending on tool design. When sharp-edge tools are used, tool life is doubled when cutting starts are slow. With rounded-cutting-edge tools, the starting speed has almost no effect. A positive feed must be used. A ceramic tip should not dwell in a cut. If this occurs, the ceramic may chip severely.

High-speed steel and cast-alloy tools should be ground on a tool grinder rather than by hand. The same is true for carbide tools; however, off-the-shelf-brazed and throwaway carbide tools often fit the rake, lead, and relief-angle requirements conveniently.

Carbide cutters are available as brazed, clamped, and throwaway tooling. Brazed tools may be purchased in standard sizes and styles as shown in Table XII, or they can be made up in the shop. The performance of mechanically clamped inserts is at least as good as that of brazed tools, and they are often recommended because of their lower cost per cutting edge.

TABLE XII. TOOL GEOMETRIES OF BRAZED CARBIDE TOOLS

Tool Geometry	Style of Tool A	B	C	D	E
Back rake	0	0	0	0	0
Side rake	7	7	0	0	0
End relief	7	7	7	7	7
Side relief	7	7	7	7	7
End-cutting-edge angle	8	15	--	50	60
Side-cutting-edge angle	0	15	--	40	30

Carbide and ceramic tools available as multiple-edge, indexable inserts are designed to be held mechanically in either positive- or negative-rake tool holders of various styles and shank sizes.

The insert is placed between a flat carbide seat in the holder and a serrated adjustable chip breaker. The clamping pressure must be evenly distributed across the top of the insert. Sometimes a shim cushion of aluminum foil (0.0015 inch) between the ceramic tip and the carbide seat may be helpful in reducing shock and in distributing the clamping forces. The general coding system for mechanical tool holders is shown in Table XIII. The tool geometries available for solid-base tool holders and suitable for turning the alloy steels and stainless steels under consideration are shown in Table XIV.

A word of caution is in order regarding tool holders. Abnormal failure of carbide or ceramic inserts can be caused by tool holders operating beyond replacement age. Worn and damaged tool holders do not provide optimum insert support or registry. They make such inserts prone to early failure (Ref. 7).

Substantial reduction in costs are claimed by users of throw-away tooling. Factors contributing to this saving are:

(1) Reduced tool-grinding costs

(2) Reduced tool-changing costs

(3) Reduced scrap

TABLE XIII. GENERAL CODING SYSTEM FOR MECHANICAL TOOL HOLDERS

Company Identification[a]	Shape of Insert	Lead Angle	Rake Angle[b]	Type Cut
( )	T	B	( )	R or L
( )	R	A	( )	R or L
( )	P	A	( )	R or L
( )	S	B	( )	R or L
( )	L	B	( )	R or L

Shape of Insert

T = triangle
R = round
P = parallogram
S = square
L = rectangle

Lead Angle or Tool Style

A = 0-degree turning
B = 15-degree lead
D = 30-degree lead
E = 45-degree lead
F = facing
G = 0-degree offset turning

Type Cut

R = right hand
L = left hand
N = neutral

(a) ( ) - Some producers place a letter here for company identification.

(b) ( ) - Some companies use the letter "T" for negative rake, "P" for positive rake, and sometimes add "S" to indicate "solid-base" holders. For example, a TATR designation denotes a tool holder for a triangular insert mounted in such a way to give a 0-degree lead angle, and a 5-degree negative rake. The "R" denotes a right-hand cut. As shown in Table XIV, 5-degree rakes are usually supplied; hence rake-angle values are not included in the tool-holder designation.

TABLE XIV. TOOL GEOMETRIES OF SOLID-BASE TOOL HOLDERS FOR THROWAWAY INSERTS

Negative-Rake Tools				Positive-Rake Tools			
Tool Angles, degrees							
Back rake, 5 Side rake, 5 End relief, 5 Side relief, 5				Back rake, 0 Side rake, 5 End relief, 5 Side relief, 5			
Tool-Holder Style[a]	Type Insert[a]	ECEA[b], degrees	SCEA[c], degrees	Tool-Holder Style[a]	Type Insert[a]	ECEA[b], degrees	SCEA[c], degrees
A	T	5	0	A	T	3	0
A	T	3	0	A	T	5	0
A	R	8	0	-	-	-	-
B	T	23	15	B	T	23	15
B	T	18	15	B	S	15	15
B	S	15	15	B	T	20	15
B	T	20	15	-	-	-	-
D	T	35	30	D	T	35	30
E	S	45	45	-	-	-	-
F	T	0	0	F	T	0	0
F	S	15	0	F	S	15	0
G	T	3	0	G	T	3	0

(a) See Table XIII for explanations.
(b) End-cutting-edge angle.
(c) Side-cutting-edge angle.

(4) Increased use of harder carbides for longer tool life or increased metal-removal rates

(5) Savings through tool standardization.

Setup Conditions. Turning operations should be conducted on a standard or heavy-duty lathe in good condition. The work should be firmly chucked in the collet of the spindle and supported by the tail stock using a live center. Machining should be done as close as possible to the spindle for minimum work overhang. A steady or follow rest should be used to add rigidity to slender parts.

The cutting tool should be held firmly in a flat-base holder with minimum overhang to avoid tool deflection. It should cut on dead center.

Cutting Speeds. High speeds can be used for the annealed nonstainless alloy steels; however, significantly lower cutting speeds must be used to obtain reasonable tool life when turning the austenitic alloys and the hardened steels.

Feed. Turning operations for these materials require constant, positive feeds throughout machining (Ref. 66). Dwelling, stopping, or a deliberate slowing up in the cut must be avoided (Ref. 7).

Feeds must be carefully chosen for these alloys (Ref. 16), and they should be as heavy as the surface-finish requirement will allow. However, the high strengths of these alloys will not allow feeds above 0.020 ipr, even where optimum tool geometry is used. This limit is imposed principally by the strength of the cutting edge (Ref. 7). On the other hand, very light feeds should not be used unless the tool demands it (Ref. 7). Feeds of 0.005 ipr or higher are usually recommended (Refs. 28,66) with average feeds ranging between 0.005 and 0.010 ipr (Ref. 7).

Depth of Cut. The choice of cut depth will depend on the amount of metal to be removed, the metal-removal rate desired, and the turning operation undertaken. In removing scale, the tool should get under the scale and cut at least 0.020 inch deeper than the tool radius. For second cuts, the nose of the tool should get below any work-hardened surface remaining from previous processing operations, although second cuts will notch the tool at the depth-of-cut line (Ref. 7). In finish turning, light cuts should be used for the best finish and the closest tolerances (Ref. 66). Cut depths up to 1/4 inch are suggested. However, depths of cut less than 1/64 inch should not be used.

Cutting Fluids. Cutting fluids are most always used during turning and boring operations to cool the tool and to aid in chip disposal. However, there is little to gain in tool life by using a coolant with ceramic tools. If used, it must be supplied copiously, or not at all. Dry cutting is also done in some instances with carbides, and usually where chip contamination is objectionable. Dry cutting, however, is not recommended for semifinishing and finishing operations.

Water-base coolants are satisfactory cutting fluids, and are usually more effective than the highly active cutting oils (Ref. 16). Synthetic chemical coolants in water give the best results, although a 1:20 soluble oil-in-water emulsion is almost as good. Soluble oils with high dilution ratios increase heat extraction but decrease lubricity (Ref. 66). Sulfurized oils and sulfochlorinated oils are still preferred by some machinists, particularly where tool "buildup" is a problem (Ref. 66).

A full, steady flow of cutting fluid should be maintained at the cutting site for maximum effect, particularly for carbides. Intermittent cooling, in this case, does more harm than good (Ref. 7).

Additional Requirements. Setup conditions such as feeds, speeds, and depths of cut are given in Table XV. Figures 10 and 11 show the tool designs used in these setups for carbide and high-speed steel tools, respectively.

The supervisor should be certain that the proper conditions have been selected before operations begin. During machining he should be assured that chips are being expelled from the cutting site as promptly as possible, particularly during boring operations. Chips lying on the surface tend to produce chatter and poor surface finishes.

The tool should be examined frequently for nicks and worn flanks. These defects promote galling, increase cutting temperature, accelerate tool wear, and increase residual stresses in the machined surface.

Arbitrary tool-changing schedules are often used to insure sharp tools. This usually means replacing carbide tools after a 0.015-inch wearland in rough turning and after a 0.010-inch wearland in finish

TABLE XV. TURNING OF NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS[a]

Alloy Group	Alloy Group Representative	Alloy Condition[d]	Carbide or Ceramic[b] Tool Grade[e]	Carbide or Ceramic[b] Tool Design[f]	Carbide or Ceramic[b] Depth of Cut[g], inch	Carbide or Ceramic[b] Feed[h], ipr	Carbide or Ceramic[b] Cutting Speed, fpm Brazed	Carbide or Ceramic[b] Cutting Speed, fpm Throwaway	High-Speed Steel[c] Tool Grade[e]	High-Speed Steel[c] Tool Design[f]	High-Speed Steel[c] Depth of Cut[g], inch	High-Speed Steel[c] Feed[h], ipr	High-Speed Steel[c] Cutting Speed, fpm
						Nonstainless Alloy Steels							
	Cr-Mo low-alloy steels												
A1	A-4130	Ann	C-6	A, B	0.25	0.015	350	425	T1, M1	G	0.25	0.015	105
		(150-230 Bhn)	C-7	A, B	0.05	0.008	425	500	T1, M1	G	0.25	0.008	140
E1	A-4130	Ann	C-6	A, B	0.25	0.015	200	275	T5, M3	H, J	0.25	0.015	45
		(350 Bhn)	C-7	A, B	0.05	0.008	260	325	T5, M3	H, J	0.05-0.06	0.008-0.009	65
	Cr-Ni-Mo low-alloy steels												
C1	A-4340	Ann	C-6	A, B	0.25	0.015	350	425	T1, M1	G	0.25	0.015	105
		(150-230 Bhn)	C-7	A, B	0.05	0.008	425	500	T1, M1	G	0.05	0.008	140
F1	A-4340	HT	C-6	A, B	0.25	0.015	200	275	T5, M3	H, J	0.25	0.015	45
		(350 Bhn)	C-7	A, B	0.05	0.008	260	325	T5, M3	H, J	0.05-0.06	0.008-0.009	65
G1	A-4340	HT	C-7	A, B	0.25	0.015	75	120	T15	K	0.25	0.015	15
		(510-560 Bhn)	Ceramic	C, D	0.063	0.009	--	220-250					
			C-8	A, B	0.05	0.008	110-150	200					
			Ceramic	C, D	0.015-0.030	0.005	--	600	T15	K	0.05	0.008	25
	5Cr-Mo-V-die steels												
D2	H-11	Ann	C-6	A, B	0.25	0.015	325	400	T1, M1	G	0.25	0.015	75
		(160-220 Bhn)	C-7		0.05	0.008	400	500	T1, M1	G	0.05	0.008	110
		HT	C-6	A, B	0.25	0.015	180	260	T15	H, J	0.25	0.015	45
F2	H-11	(350 Bhn)	--	--	0.10	0.009	200	--	--	--	--	--	--
			C-7	A, B	0.05	0.008	250	325	T15	H, J	0.05-0.06	0.008-0.009	55-60
		HT	C-7	A, B	0.25	0.010	75	95	T15	K	0.25	0.010	15
G2	H-11	(515-560 Bhn)	C-8	A, B	0.03-0.10	0.004-0.009	100-120	140	T15	K	0.05-0.060	0.007-0.009	20
	Maraging steels												
D3	18Ni-Co-Mo	Ann	C-2, C-6	B	0.062	0.009	--	450	M2	J, L	0.062	0.009	70-80
		(302-341 Bhn)	C-3	B	0.062	0.009	--	475	--	--	--	--	--
			C-8	B	0.062	0.009	--	500	T15	J, L	0.062	0.009	90-95
		HT	C-2	B	0.062	0.005-0.009	--	180-190	M2	J, M	0.062	0.005	45
G1		(52 R_C)	C-3	B	0.062	0.009	--	275	M44, T15	J, M	0.062	0.005	60
	Cr-Ni-Mo steel												
G2	D6a	HT	C-4	B	0.062	0.005	--	75	--	--	--	--	--
		(56 R_C)											
		(58 R_C)	Ceramic 030	C	0.062	0.005	--	175	--	--	--	--	--
						Stainless Steel Alloys							
	Straight-chromium grades												
B4	Type 405	Ann	C-6	A, E, F	0.25	0.015-0.018	130-300	400	T5, M3	N, O	0.25	0.008-0.015	80-100
		(150-200 Bhn)	C-7	A, E, F	0.05	0.005-0.008	200-400	450	T5, M3	N, O	0.05	0.005-0.008	80-130
B5	Type 410	Ann	C-6	A, E, F	0.25	0.015-0.018	130-350	425	T5, M3	N, O	0.05	0.015	90
		(160-220 Bhn)	C-7	A, E, F	0.05	0.005-0.008	200-400	450	T5, M3	N, O	0.050-0.062	0.008-0.009	115-125
F5	Type 410	HT	C-6	A, E, F	0.25	0.015	175	225	T1, M1	H, K	0.25	0.015	45
		(300-350 Bhn)	C-7	A, E, F	0.05-0.10	0.008-0.009	200-250	275	T1, M1	H, K	0.50-0.060	0.008-0.009	60
		(415 Bhn)	C-2	C	0.10	0.009	175	--	T1	H, K	0.060	0.009	45

TABLE XV. (Continued)

Alloy			Carbide or Ceramic(b)						High-Speed Steel(c)				
			Tool				Cutting Speed, fpm		Tool				
Group	Group Representative	Alloy Condition(d)	Grade(e)	Design(f)	Depth of Cut(g), inch	Feed(h), ipr	Brazed	Throwaway	Grade(e)	Design(f)	Depth of Cut(g), inch	Feed(h), ipr	Cutting Speed, fpm
						Stainless Steel Alloys (Continued)							
Straight-chromium grades (Continued)													
D5	Type 440 B	Ann	C-6	A, E, F	0.25	0.008-0.015	150-300	375	T5, M3	N, O	0.25	0.008-0.015	30-60
	C	(215-260 Bhn)	C-7	A, E, F	0.05	0.005-0.008	200-350	400	T5, M3	N, O	0.05	0.005-0.008	45-75
G5	Type 440 B	HT	C-6	A, E, F	0.25	0.010-0.015	90	100	T15	H, K	0.25	0.008-0.015	30
	C	(375-440 Bhn)	C-7	A, E, F	0.05	0.008	125	175	T15	H, K	0.05	0.008	45
Precipitation-hardenable grades													
D6	17-7 PH	Ann	C-6	A, E	0.10-0.25	0.009-0.015	180-300	400	T1, M1	H, K	0.25	0.009-0.015	65-70
		(160-180 Bhn)	C-7	A, E	0.05	0.008	300-375	475	T1, M1	H, K	0.050-0.060	0.008-0.009	70-95
				--	--	--	--	--	--	--	--	0.003-0.005	100-120
		HT	C-6	A, E	0.25	0.015	175	250	T15	H, K	0.25	0.015	30
F6		(330-440 Bhn)	C-2	--	0.10	0.009	150	--	--	--	--	--	--
			C-7	A, E	0.05	0.008	200	275	T15	H, K	0.05-0.06	0.008-0.009	40-45
Chromium-nickel grades													
D7	Type 347	Ann	C-2	A, E	0.25	0.008-0.018	180-250	275	T5, M3	N, O	0.25	0.008-0.015	60-65
		(160-220 Bhn)	C-3	A, E	0.05	0.005-0.008	150-300	350	T5, M3	N, O	0.05	0.003-0.008	95-120
	Type 302		--	--	--	--	--	--	T1	--	0.062	0.009	90
						Austenitic Stainless Steel Super Alloys							
Nonheat-treatable grades													
D8	19-9DL	ST							T5, M3	H, N	0.25	0.010	40
		(200 Bhn)	C-2	A, E	0.25	0.010	100	150-200	T5, M3	H, N	0.050	0.008	50
			C-2, C-3	A, E	0.05-0.10	0.008-0.009	150-160	--	T1	--	0.060	0.009	30
			--	--	0.125	0.007-0.015	150-200	--	--	--	--	--	--
			--	--	0.06	0.05-0.010	175-225	--	--	--	--	--	--
E8	Timken	ST	C-6	A, E	0.125	0.007-0.015	60-100	--	--	H, N	0.06-0.1	0.030	40-45
	16-25-6		C-7a	A, E	0.125	0.010-0.015	75-100	--	--	--	--	--	--
			C-7a, C-8	A, E	0.05	0.005-0.010	100-175	--					
Age-hardenable grades													
D9	Discaloy	STA	C-2, C-3	A, E	0.025	0.007-0.015	100-200	--	--	--	--	--	--
			C-3, C-4	--	0.06	0.005-0.010	175-200	--	--	--	--	--	--
E9	A-286	ST			--	--	--	--	T15	H, N	0.062	0.009	45
		(180-220 Bhn)	C-2, C-3	A, E	0.05	0.008	150	200	T5, M3	H, N	0.25	0.010	40
			--	--	--	--	--	--	T5, M3	H, N	0.05	0.009	50
		STA	C-7a, C-2	A, E	0.125-0.25	0.010-0.015	60-100	--	T15	H	0.25	0.01	45
		(280-320 Bhn)	C-3	A, E	0.10	0.009	--	150	--	--	0.062	0.009	40
			C-7a, C-8	A, E	0.05	0.005-0.010	90-160	225	--	--	--	--	--
			C-3, C-4										

Footnotes appear on following page.

Footnotes for Table XV

(a) From References 1, 2, 6, 7, 15, 16, 28-31, 33, 46, 49, 55-59, 61-63.
(b) Cutting fluids for carbide tools are:

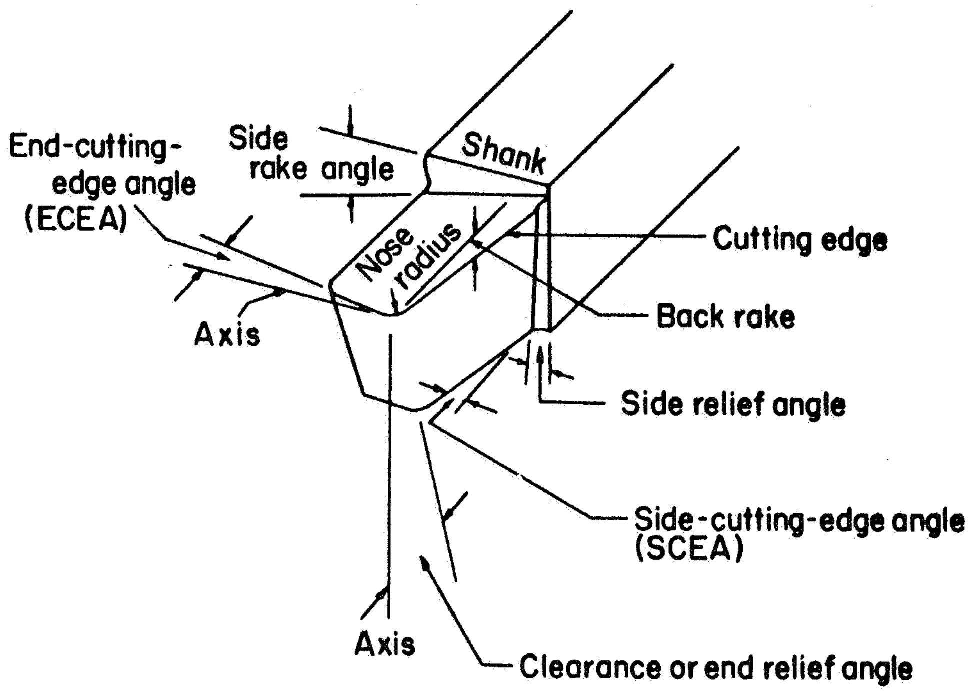
Alloy	Cutting Fluid
Nonstainless alloy steels	
Low-alloy steels (up to 350 Bhn)	IIa, IIIa, IV
Low-alloy steels (510-560 Bhn)	I, V (dry)
5Cr-Mo-V die steels	I, V (dry)
Maraging steels	I
D6a (HT 56-58 R_C	V (dry)
Ceramic tools are used dry	(V)
Stainless steel alloys	I, V
Stainless steel superalloys	I, V

(c) Cutting fluids for high-speed steel tools are:

Alloy	Cutting Fluid
Nonstainless alloy steels	
Low-alloy and die steels	
Annealed	I, IIa
Heat treated (350 Bhn)	I
Heat treated (515 Bhn)	IIa, IIIa, IV
Maraging steels	I
Stainless steel alloys	
All grades	
Annealed	I
Heat treated	IIa, IIIa, IV
Stainless steel superalloys	I

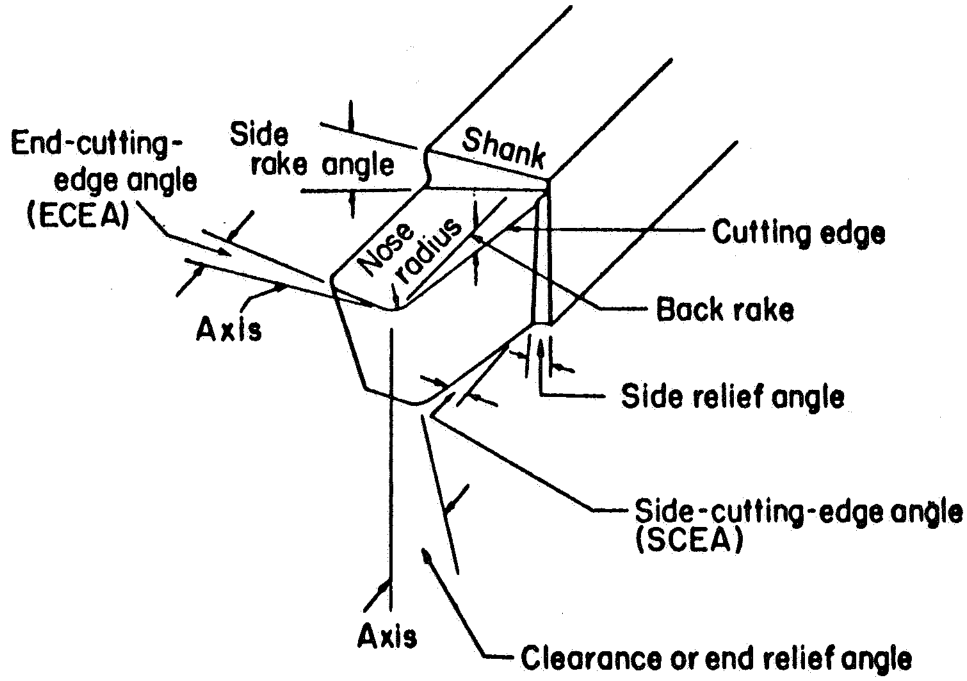
See page 25 for specific types.

(d) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.
(e) CISC designation for carbides (see page 15); AISI designation for high-speed steels (see page 18).
(f) See Figures 10 and 11 for tool angles involved.
(g) Cut depths of 1/8 inch and more do not give the best tool life, especially for steel hardened to 500-560 Bhn. Hence, they are generally listed below 1/8 inch.
(h) Carbide tools usually can take feeds between 0.0035 and 0.040 ipr depending on the hardness of the steel being machined. When they operate below 0.003 ipr, spalling or crumbling of the cutting edge may occur on very hard materials.



	Tool-Geometry Code					
	A	B	C	D	E	F
Tool angles, degrees			(Ceramic)	(Ceramic)		
Back rake	0	-5	-5	-5	0	0 to -5
Side rake	5 to 6	-5	-5	-5	5	5 to -7
End relief	5	5	5	7	5	5 to 10
Side relief	5	5	5	7	5	5 to 8
End-cutting edge	5	15	15	15	5	5 to 15
Side-cutting edge (lead)	15	15	15	15	15	5 to 15
Nose radius, inch	0.032	0.032	0.032	0.032	0.032	--

FIGURE 10. TOOL-GEOMETRY NOMENCLATURE AND DATA FOR CARBIDE TOOLS



	Tool-Geometry Code							
	G	H	J	K	L	M	N	O
Tool angles, degrees								
Back rake	8 to 10	0	0	0	0 to 5	0 to 3	5	5 to 10
Side rake	10 to 12	15	8 to 10	5	10 to 15	0 to 3	6 to 8	5 to 10
End relief	6 to 8	5	5	5	7	7	6	5 to 10
Side relief	6 to 8	5	5	5	7	7	6	5 to 15
End-cutting edge	5	5	5	5	5 to 7	5 to 7	6	4 to 15
Side-cutting edge (lead)	15	0	15	15	15 to 20	15 to 20	15	5 to 15
Nose radius, inch	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03

FIGURE 11. TOOL-GEOMETRY NOMENCLATURE AND DATA FOR HIGH-SPEED STEEL TOOLS

turning. High-speed steel tools are usually replaced after a wearland of 0.030 inch has developed.

If periodic interruptions are made in a machining operation before these maximum wearlands occur, any smeared metal, nicks, or crevices found on the cutting edge should be removed by honing before machining is resumed.

After certain turning operations, parts may require stress relieving. The following treatments are suggested:

(1) Anneal after rough machining

(2) Stress relieve thin-wall parts after semifinish operations

(3) Stress relieve all finished parts.

DRILLING

Introduction. Drilling can be a difficult machining operation to perform on high-strength materials if good practices are not used (Ref. 66). In the first place, the thrust and torque forces are higher than those needed for drilling annealed steels and aluminum alloys. Secondly, the center web of the drill extrudes rather than cuts metal in its vicinity. Consequently, the bottom of the hole may work harden enough to cause early drill failure, especially in the case of the highly work-hardenable stainless steel superalloys. Work hardening can be minimized by using sharp drills with thin webs, together with constant, positive feeds throughout drilling.

Difficulties resulting from poor drilling action include out-of-round, tapered, or smeared holes all of which cause problems in subsequent reaming or tapping operations. These difficulties can be minimized by employing five important techniques as follows: designing holes as shallow as possible; using short, sharp drills with large flutes and special points; flushing the tool-chip contact site with suitable cutting fluids; employing low speeds and positive feeds; and supporting the exit side of through holes where burrs otherwise would form (Refs. 29,48,64).

Machine Tools. Drilling machines must be sturdy and rigid enough to withstand the thrust and torque forces built up during the cutting. Hence, the spindle overhang should be no greater than necessary for a given operation. Excessive clearances in spindle bearings cannot be tolerated; the radial and thrust bearings should be good enough to minimize runout and end play. Finally, the feed mechanism should be free of backlash in order to reduce the strain on the drill when it breaks through the workpiece.

Machines for drilling operations are made in many different types and sizes. Size or capacity is generally expressed either in terms of the largest diameter disk, the center of which is to be drilled, or in horsepower. Heavy-duty machines are exceptions. They are specified as the distance from the supporting column to the centerline of the chuck. The horsepower rating is that usually needed to drill cast iron with the maximum drill diameter (Ref. 67). Suitable sizes of machines for drilling nickel and cobalt alloys include:

(1) Upright Drill No. 3 or No. 4

(2) Upright Drill, production: 21-inch heavy duty, 5 hp

(3) Upright Drill, production: 24-inch heavy duty, 7-1/2 hp

(4) Upright Drill, production: 10 hp.

Industry also has requirements for drilling parts at assembly locations. These needs are fulfilled by portable power-feed, air-drilling machines. Modern units incorporate positive mechanical-feed mechanisms, depth control, and automatic return (Ref. 68). Some are self-supporting and self-indexing. Low-speed, high-torque drill motors are needed. Spindle speeds between 230 and 550 rpm at 90 psi air pressure seem appropriate for high-speed drills. Thrust between 320 and 1000 pounds are available on some portable drilling machines.

Portable drill units include the Keller K-Matic, the Keller Airfeedrill, the Winslow Spacematic, and the Quackenbush designs (Refs. 68-70). The Keller K-Matic incorporates a positive, mechanical-feed mechanism, a depth-control device, and an automatic-return provision. The Keller Airfeedrill utilizes a variable pneumatic feed. The Winslow Spacematic is a self-supporting, self-indexing unit capable of drilling and countersinking in one operation (Ref. 68).

Quackenbush portable drilling machines also can be used. One style is a 500 rpm pneumatic powered unit with a positive mechanical-feed mechanism capable of providing 0.001 ipr feed (Ref. 69).

Drills. Drill strength and rigidity are highly important factors for the successful drilling of nonstainless alloy steels and stainless steel (Refs. 71,72). Generally speaking, drills are made from special high-speed steels, and incorporate helical designs, polished flutes, and short lengths. Drills should be the heavy-duty type with heavy webs (Refs. 31,72). The length of the drill should be kept as short as possible, not much longer than the intended hole, to increase columnar rigidity and decrease torsional vibration that causes chatter and chipping.

A heavy-duty stub-type screw machine drill is recommended for drilling operations on workpieces other than sheet (Ref. 29). For deep holes, oil-feeding drills, gun drills, or a sequential series of short drills of various lengths may be employed. Oil-feeding drills cool, lubricate, minimize welding, and help in chip removal. The NAS 907, Type B or C drill can be used for drilling sheet material.

Drill Design. Drill geometry is a sensitive and important factor in the successful drilling of these high-strength materials. Two ostensibly similar drills can have substantially different tool lives - either because of minute differences in geometry or because of thermal damage during grinding. Hence, uniform grinds are needed for reproducible tool lives (Ref. 29).

The choice of helix angles will depend on the job conditions and on the alloy being drilled. Both low-helix angles (12 degrees) and high-helix angles (33 degrees) can be used. For example, low-helix, heavy-duty-type drills have outperformed high-helix Type 3300 and regular-helix Type C drills when drilling 1/2-inch through holes in SAE 4340 hardened to 52 R_C. On the other hand, the 3300 style performs well in drilling shallower holes (1/8-inch through holes) (Ref. 71). Generally speaking, drills with 28-degree helix angles represented by the regular helix heavy-duty types can be used for most drilling applications (Ref. 64).

The choice of relief angles is extremely important to drill life. Small angles tend to cause excessive pickup, while excessively large angles will weaken the cutting edge. Relief angles between 7 and 12 degrees have been used successfully by different investigators (Refs. 29,31). Drills with 118-degree point angles may have large relief angles up to 12 degrees. The flatter point angles (from 130 to 140 degrees) can be used with relief angles running moderately low, for example, around 6 degrees.

Point angles have a marked effect on drill life. The choice of 90, 118, or 135 degrees will depend on the feed, drill size, and type of workpiece. The flatter points tend to develop lower thrust forces than 90-degree points and also provide maximum support in the critical area of the chisel edge, which can become damaged from high axial loads on the drill (Ref. 71). Occasionally the cutting corners of the drill are chamfered (with a smaller angle than the drill-point angle) to protect them from premature breakage. Thus a double angle, 118/90 degrees, can give very good results (Ref. 54).

Special point grinds used are crankshaft, notch-type drills; and split points with positive-rake notchings (Ref. 31). Crankshaft points minimize work hardening caused by the extrusion action of the conventional chisel point (Ref. 73), and are useful for deep holes (Ref. 31). High-tensile-type notch and split points also give good performance (Ref. 71).

Webs are often thinned to reduce pressure at the drill point during drilling. However when doing so, the effective rake angles of the cutting edges should not be altered.

Drill Quality. The geometry of drills should be checked against recommendations before they are used. If necessary, drills should be reground accurately on a drill grinder, and the point angle, relief angle, and web thickness rechecked. Drills should never be hand sharpened.

The apex of the point angle should be held accurately to the centerline of the drill, and the cutting lips should have the same slope. This combination avoids uneven chip formation, drill deflection, and oversized holes (Ref. 74). When dull drills are reconditioned resharpening the point alone is not always adequate. The entire drill should be reconditioned to insure conformance with recommended drill geometry. Machine ground points with fine finishes give the best tool life (Ref. 68). A surface treatment such as chromium plating or a black oxide coating of the flutes may minimize welding of chips to the flutes.

Tool Materials. Molybdenum-tungsten grades of high-speed steels are generally used for drilling the nonstainless alloy steels and stainless steels (Refs. 16,31,64). With proper care, carbide drills can be used on ultrahigh-hardness steels. However, their high cost coupled with their brittleness limits their use. Furthermore, only small amounts of lip and corner wear are permissible with carbide drills (Ref. 29).

Conventional molybdenum-tungsten high-speed steel drills (M1, M2, M10) are usually used in production. Cobalt high-speed steels (T15) generally perform better than the standard grades of high-speed steel (Ref. 29). The M33 grade also performs very well, as does the ultrahard M41 grade (Refs. 16,64).

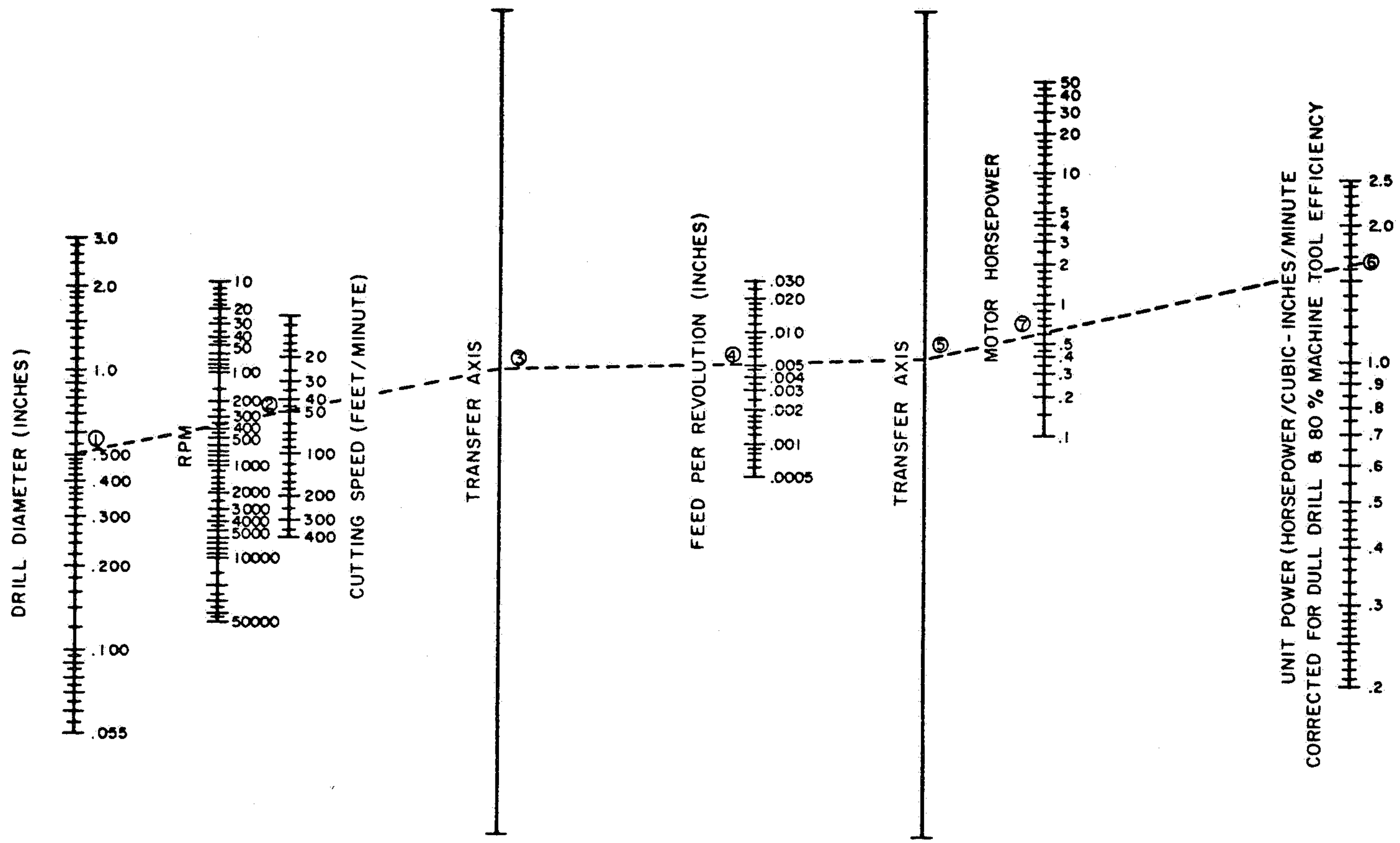
Setup Conditions. Setup conditions selected for drilling should provide overall setup rigidity, and sufficient spindle power to maintain drill speeds during cutting. Figure 12 presents an alignment chart for determining horsepower at various feeds and speeds (Ref. 63).

Thin sheet-metal parts must be properly supported at the point of thrust. This can be done with backup blocks of AISI 1010 or 1020 steel. Where this is not possible because of part configuration, a low-melting-point alloy can be cast about the part (Ref. 29). Proper alignment of the supported work and drill is also necessary to prevent premature drill breakage.

Drill rigidity is also important. Drills should be as short as possible. Heavy-duty stub drills should be used instead of jobbers-length drills to prevent deflection that causes out-of-round holes (Ref. 29). Drill jigs and bushings are used whenever added rigidity is needed. For deep-hole drilling, several lengths of short drills may be employed in sequence. A drill bushing should be incorporates, if possible, in the setup for additional rigidity. When drilling stacked sheet, the sheets should be clamped securely with clamping plates to eliminate gaps between sheets.

Setup also involves speeds, feeds, and coolants. Successful drilling of these materials depends on being able to reduce the temperature at the cutting lips. This can be accomplished by using low cutting speeds, employing proper feed rates, and supplying adequate cooling at the cutting site.

Cutting Speed. Since the cutting zone is confined, drilling requires low speeds for minimum cutting temperature. The choice of speed used will depend largely on the strength level of the



HORSEPOWER = 3 X DRILL DIAMETER X SPEED X FEED X UNIT POWER

Cutting Conditions:

Drill Diameter = .500 Feed: .005 ipr

Cutting Speed 50 fpm Unit Power: 1.6 hp/in.^{2}/min

To Determine Motor Horsepower:

Connect drill diameter ① with cutting speed ② to obtain point ③ on transfer axis. Connect ③ with feed ④ tc obtain point ⑤ on transfer axis. Connect ⑤ with unit power ⑥ to obtain .60 horsepower at motor, point ⑦

FIGURE 12. ALIGNMENT CHART FOR DETERMINING MOTOR HORSEPOWER IN DRILLING OPERATIONS (REF. 63)

material and the nature of the workpiece. Thus, speeds may range between 10 and 120 fpm for A-286 and 410 stainless steels, respectively (Refs. 64,71). Speeds should be lower for deep holes to compensate for inadequate lubrication and cooling (Ref. 29). Speeds also should be lowered as feed increases. In large drills low speeds and heavy feeds give the best production rate (Ref. 29).

Feed. The best approach in drilling high-strength steels and stainless steels is to keep the drill cutting. The drill should never ride in the hole without cutting since the rubbing action promotes work hardening, galling of the lips, and rapid dulling of the cutting edge. The best technique is to use equipment having positive, mechanical feeds.

Assembly drilling of sheet should also be done with portable power drills having positive-feed arrangements. This equipment was described on page 68.

Hand drilling is not recommended. The high axial thrust required to keep the drill cutting, especially in solution-treated and aged alloys, can cause rapid operator fatigue. Furthermore, allowing the drill to advance rapidly on breakthrough, as is generally the case with hand feeding, will seriously shorten drill life.

The selection of feeds depends largely on the size of the drill being used. Generally, a feed range of 0.0005 to 0.005 ipr is used for drills up to 1/4-inch diameter. Drills 1/4 to 3/4-inch diameter will use heavier feeds depending on the alloy (Refs. 64,71).

Cutting Fluids. Drilling the alloy and stainless steels requires the use of cutting fluids with good lubricating and antiweld properties (Ref. 71).

Lubricating and chemically active cutting fluids such as sulfurized oils or sulfurized-chlorinated oils are recommended (Refs. 29, 71). Sulfochlorinated oils are better than the straight chlorinated oils or a water-soluble mixture (Ref. 71). Highly sulfurized oils are often diluted 1:1 with light machine oil, particularly when carbide tools are used (Ref. 16).

A steady, full flow of fluid externally applied is used. However, a limiting hole depth of twice the diameter seems to exist for external applications of cutting fluids. Hence, oil-feeding drills work best for deep holes.

Additional Requirements. Setup conditions such as speeds, feeds, and cutting fluids are given in Table XVI. Figure 13 shows the drill designs used in these setups.

The first consideration in planning a drilling setup is to select a drilling machine on the basis of the rigidity, mechanical condition, available power, and feed/speed ranges suitable for the steel to be drilled. The next consideration would be the selection of drills, bushings, fixtures, and cutting fluids.

When starting the drilling operation, the drill should be up to the required speed and under positive feed as it contacts the work. The drill must be sharp, and the proposed hole location should be marked with a triangular center punch. A circular-type center punch must not be used since the drill will not start because of the work-hardened surface produced.

The margin of the drill should be examined periodically for smearing as well as for breakdowns that might occur at the outer corner of the lips. An arbitrary drill replacement point should be established to prevent work and drill spoilage.

The drill should be pulled out of the hole frequently to free it from chips and to permit intermittent cooling of the drill unless the cutting fluid successfully flushes away the chips.

When drilling holes deeper than the diameter of the drill, retract the drill once for each 1/2 diameter of drill advance to clear the flutes. Retract the drill at the same time the feed stops to minimize dwell. Reengage drill quickly, but carefully, with the drill up to speed and under positive feed.

When drilling "through holes" do not drill all the way through on a continuous feed. Instead, retract drill before breakthrough and flush the drill and hole to remove the chips. Then return drill under positive feed and drill through carefully avoiding any "feed surge" at breakthrough.

Drilled holes will require reaming to meet the tolerances of Class I holes, unless a bushing is used immediately adjacent to the part. Drilled holes in sheet will probably require exit-side deburring.

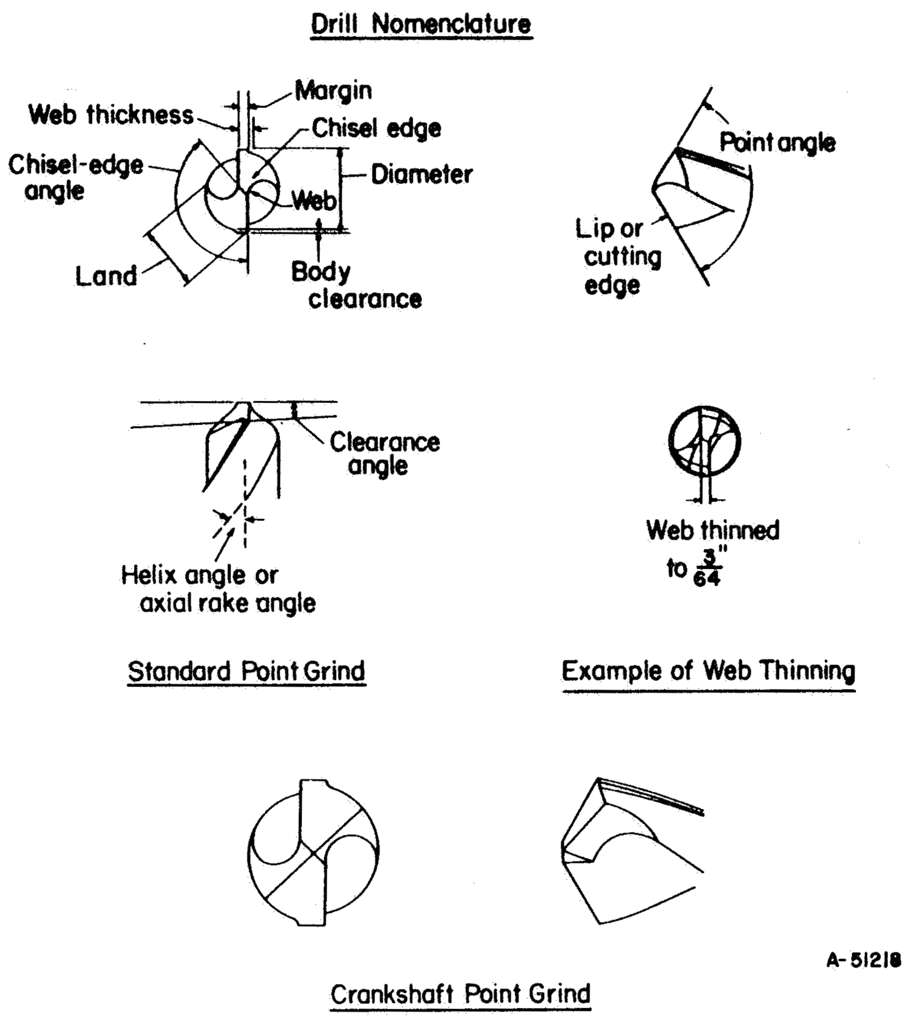
TABLE XVI. DRILLING DATA FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS[a]

Alloy Group	Alloy Group Representative	Alloy Condition(b)	Carbide and High-Speed Steel Drills: Grade(c)	Design(d)	Cutting Speed(e), fpm	Cutting Fluid	Feed for Drill Diameter Shown, ipr — Nominal Drill Diameter, inch: 1/8	1/4	1/2	3/4	1	1-1/2	2
						Nonstainless Alloy Steels							
	Cr-Mo low-alloy steels												
A1	A-4130	Ann (150-230 Bhn)	M1, M10	A	60	I, IIa	0.002	0.004	0.006	0.009	0.012	0.012	0.015
E1	A-4130	HT	M1, M10	B	45	IIa, IIIa, IV	0.001	0.003	0.005	0.007.	0.009	0.010	0.015
		(350 Bhn)	M2	B	110	--	--	0.002	--	--	--	--	--
			M2	B	45	--	--	0.005	--	--	--	--	--
	Cr-Ni-Mo low-alloy steels												
C1	A-4340	Ann (150-230 Bhn)	M1, M10	A	60	I, IIa	0.002	0.004	0.006	0.009	0.012	0.012	0.015
F1	A-4340	HT	M1, M10	B	45	IIa, IIIa, IV	0.001	0.003	0.005	0.007	0.009	0.010	0.015
		(350 Bhn)	M2	B	70	--	--	0.002	--	--	--	--	--
			M2	B	45	--	--	0.005	--	--	--	--	--
G1	A-4340	HT (45 R_C)	M7, M33	C	40	I, IV	--	0.001-0.003	--	--	--	--	--
		HT	T15, M33, M7	B, D	20-30	IIa, IIIa, IV	0.0005	0.001	0.003	0.004	--	--	--
		(510-560 Bhn)	T15, M7	C	20	IV	--	0.0006	--	--	--	--	--
			Carbide	--	90	I	--	0.001	--	--	--	--	--
	5Cr-Mo-V die steels												
D2	H-11	Ann (160-220 Bhn)	M1, M10	A	55	I, IIa	0.0015	0.003	0.006	0.009	0.012	0.015	0.020
F2	H-11	HT	M2	B	40	IIa, IIIa, IV	0.001	0.002	0.005	0.007	0.009	0.012	0.015
		(350 Bhn)	M2	B	60	--	--	0.002	--	--	--	--	--
			M2	B	50	--	--	0.005	--	--	--	--	--
G2	H-11	HT	M33	B, D	20	--	--	0.0035	--	--	--	--	--
		(515-560 Bhn)	T15, M33	B, D	30-40	I, IIa	0.0005	0.001	0.003	0.003	0.005	--	--
			Carbide-C-2	--	70	I	--	0.0015	--		--	--	--
	Maraging steels												
D3	18Ni-Co-Mo	HR	M1, M2, M33, T15	A, E	60-70	IV	0.0015	0.0025	0.006	0.011	0.012	--	--
		HR-Ann	M1, M2, M33, T15	A, E	65-85	IV	0.0015	0.0025	0.006	0.011	0.012	--	--
G1		HR-Mar.	M1, M2, M33, T15	A, E	20-25	IV	0.001	0.002	0.005	0.005	0.009	--	--
	Cr-Ni-Mo steel												
G2	D6a	HT 56-58 R_C	Carbide-C-2	F	115	IIIa	--	0.001	--	--	--	--	--
						Stainless Steel Alloys							
	Straight-chromium grades												
B4	Type 405	Ann (150-200 Bhn)	M1, M10	A, G	40-120	I, IIa	0.001	0.003	0.005	0.010	0.012	0.015	0.020
B5	Type 410	Ann (160-220 Bhn)	M1, M10	G	35-120	I, IIa	0.001	0.003	0.005	0.010	0.012	0.015	0.020
F5	Type 410	HT (300-350 Bhn)	M2	A, B	30-110	IIa, IIIa, IV	0.001	0.002	0.003	0.003	0.005	--	--
		HT (415 Bhn)	T15, M33	A, B	40-50	IIa		0.002					

TABLE XVI. (Continued)

Alloy Group	Alloy Group Representative	Alloy Condition(b)	Carbide and High-Speed Steel Drills: Grade(c)	Design(d)	Cutting Speed(e), fpm	Cutting Fluid	Feed for Drill Diameter Shown, ipr — Nominal Drill Diameter, inch: 1/8	1/4	1/2	3/4	1	1-1/2	2
					Stainless Steel Alloys (Continued)								
	Straight-chromium grades (Continued)												
D5	Type 440 C	Ann (215-260 Bhn)	M1, M10	G	20-50	I, IIa	0.001	0.003	0.005	0.010	0.012	0.015	0.020
G5	Type 440 C	HT (375-440 Bhn)	T15, M33	A, B	20	IIa, IIIa, IV	0.001	0.002	0.003	0.003	0.005	--	--
	Precipitation-hardenable grades												
D6	17-7 PH	Ann 160-180 Bhn	M1, M10	A	40-60	I, IIa	0.001	0.003	0.005	0.010	0.012	0.015	0.020
			M2	A	115			0.002					
			M2	A	100			0.005					
F6	17-7 PH	HT (380-440 Bhn)	M2	A	20-25	IIa, IIIa, IV	0.001	0.002	0.003	0.003	0.005	--	--
			M1	A	40	IV				0.005			
	Chromium-nickel grades												
D7	Type 347	Ann 160-220 Bhn	M1, M10	A	30	I, IIa	0.001	0.002	0.004	0.008	0.010	0.015	0.020
	302	Ann (170 Bhn)	M1, M10	A	70	--	--	0.002	--	--	--	--	--
			M1, M10	A	70	--	--	0.005	--	--	--	--	--
					Stainless Steel Superalloys								
	Nonheat-treatable grades												
D8	19-9 DL	ST (180-220 Bhn)	T15, M33	A	20	IIa, IIIa, IV	0.0005	0.001	0.003	0.005	0.007	--	--
			M2	A	50	--	--	0.002	--	--	--	--	--
			M2	A	50	--	--	0.005	--	--	--	--	--
E8	Timken 16-25-6	ST	T15, M33	A	10-20	IIa, IIIa, IV	0.001	0.002	0.004	0.007	0.010	--	--
	Age-hardenable grades												
E9	A-286	ST (180-220 Bhn)	T15, M33	A	10-20	IIa, IIIa, IV	0.0005	0.001	0.003	0.005	0.007	--	--
			M2	A	70	--	--	0.005	--	--	--	--	--
			M2	A	90	--	--	0.002	--	--	--	--	--
		STA (280-320 Bhn)	--	A	10-20	IIa, IIIa, IV	0.001	0.002	0.004	0.007	0.010	--	--

(a) From References 15, 16, 29, 31, 49, 54-57, 59, 61-63, 71, 72, 74.
(b) Ann = annealed; HT = heat treated; HR = hot rolled; HR-Ann = hot rolled and annealed; HR-Mar. = hot rolled and maraged; ST = solution treated; STA = solution treated and aged.
(c) AISI designations for high-speed steels (page 18); CISC designations for carbides (see page 15).
(d) See Figure 13 for tool angles involved.
(e) When drilling maraging steels,
  (1) Operate drills below 1/4-inch diameter at or 20 per cent below the minimum speeds (fpm) cited. The feed (ipr) for drills below 1/8 inch ought to be below 0.0015 inch. The feed should be such that the drill produces chips, not powder, at a speed adjusted to the strength of the drill (Ref. 75).
  (2) Operate drills 1/4 inch to 3/4 inch inclusive at the maximum speeds shown. The speed for drills above 3/4 inch to 1 inch ought to approach the minimum speeds shown. The minimum speeds are recommended for drills above 1-inch diameter (Ref. 75).



Drill Elements	Drill-Geometry Code A	B	C	D	E	F	G	H
						(Carbide)		
Helix angle, degrees	24-32	24-32	28	29	28	0 Helix 10 Radial rake	Standard	28
Clearance angle, degrees	7-10	7-10 7-9		7	12	10	6-12	
Point angle, degrees	118	118-135	118/90	90	118	118	130-140	135
Type point	Standard	Crankshaft	Split			Notched	Standard or crankshaft	Split

FIGURE 13. DRILL NOMENCLATURE AND TOOL ANGLES USED

All assembly drilling should be done using portable, fixed-feed, jig-mounted drilling machines.

TAPPING

Introduction. Tapping is one of the most difficult machining operations performed on hardened alloy steels and stainless steel alloys. Although tapping techniques for these materials are essentially the same, certain modifications are needed in individual cases depending on the cutting characteristics of the specific material being tapped. These modifications include the preparation of taps, the design of the holes, and the adjustment of tapping speeds.

The basic problems in tapping the hardened steels result from their high shear strengths plus the extreme abrasiveness of the chips against the cutting edges as the chip is formed. The problems of tapping the austenitic and semiaustenitic stainless alloys involve a sluggish chip flow, severe work hardening, and significant galling/welding action.

As taps dull and cutting temperatures rise, metal welds on the cutting edges and flanks of the tap. The immediate consequence is that excess metal is removed to cause oversized holes and rough threads. Galling also increases friction and torque requirements. The additional torsional strain distorts the lead of the tap, and increases the tapping stresses until the tap seizes and breaks. The more ductile alloys tend to flow into the roots of the tap profile and cause seizure. Shank breakage from high torque is a common tap failure (Ref. 29).

Tapping difficulties in high-strength materials can be minimized by reducing the thread requirements to ranges suitable for specific applications. The thread depths usually lie somewhere in an overall range of 50 to 75 percent. Suitable thread lengths involve tapping the fewest threads the design will allow (Ref. 7).

Designers should also avoid specifying blind holes or through holes with lengths exceeding one and a half times the tap diameter. In both cases, the chips are confined and can cause rough threads and broken taps. Some relaxation in class-of-fit tolerances also should be considered when difficult materials must be tapped.

The tapping operation, itself, requires sharp taps of modified conventional design, low tapping speeds, and an effective tapping lubricant to minimize seizure.

Tapping Machines. A lead-screw tapping machine is recommended to insure proper lead, a regulated torque, and a uniform hole size. Lead-screw tapping heads should be equipped with friction clutches. The clutch should prevent tap breakage when galling occurs since a very small amount of smear may result in immediate tap breakage (Ref. 48).

Electropneumatic oscillating-type tapping machines when properly set cannot break a tap. Before any force is applied that might break a tap, the forward motion is interrupted and reversed. The tap is driven by balanced spiral springs and the tension is set just under the static breaking torque of the size of the tap being used. When the tap meets excessive resistance (which would ordinarily break the tap) the machine automatically reverses 1/2 revolution and then goes forward again (Refs. 54,76).

Tapping machines should be rigid, accurate, and sensitive. Machine tapping, unless done on a sensitive machine, by a competent operator, can result in excessive tap breakage and poor-quality work.

Taps and Their Modifications. A number of different types of taps have been used successfully, including the taper, plug, spiral-pointed, and spiral-fluted designs. These taps are illustrated in Figure 14.

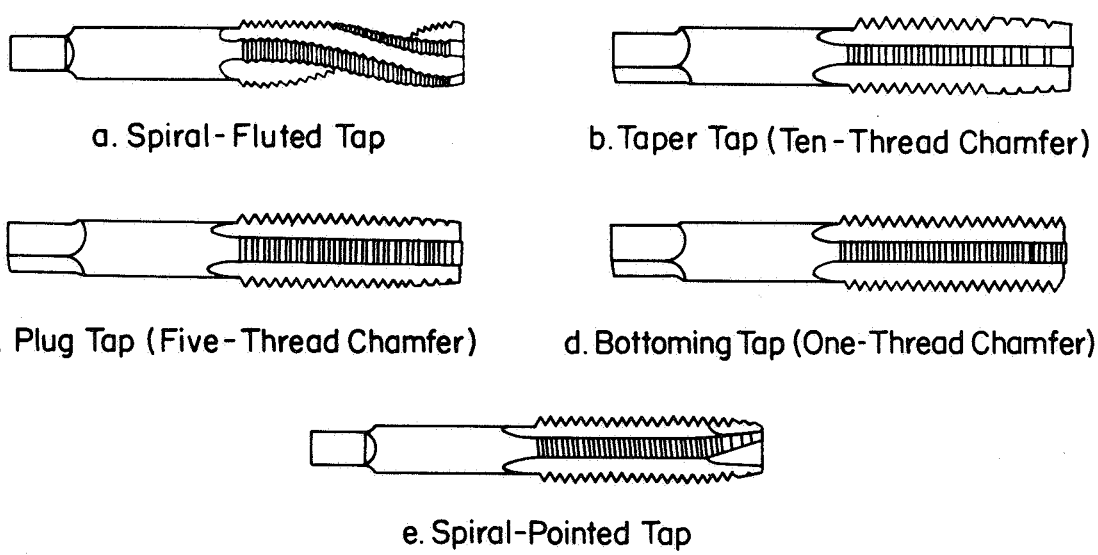


FIGURE 14. STYLES OF TAPS

The spiral-pointed and spiral-fluted taps are particularly desirable when tapping the annealed materials because they provide more adequate chip relief. Their inherent shearing action produces the least amount of resistance to thrust. Furthermore, the entering angle deflects the chips so that they curl ahead of the tap. This minimizes packing in the flutes, a frequent cause of tap breakage (Ref. 77). Those of right-hand design on a right-hand thread will carry the cuttings up and out of the hole and are therefore advantageous on blind holes. With the spiral angle opposite to that of the thread, the cuttings are forced ahead of the tap, which is beneficial in the case of through holes (Ref. 15). However, a spiral-pointed tap cannot be expected to propel chips forward in holes that are more than 2 diameters long.

Conventional plug taps may be used for hand tapping maraging steels in any condition of heat treatment. The use of a taper tap (with a smaller pitch diameter than the plug tap) should precede the plug tap (Ref. 33). Serial-type taps are suggested for hand tapping when the thread is tapped in two or more operations (Ref. 33).

If rubbing between the relief surface and the threaded hole is encountered during tapping, it may be decreased by

(1) Using interrupted threads with alternate teeth missing

(2) Grinding away the trailing edge of the tap

(3) Grinding axial grooves in the thread crests along the full length of the lands

(4) Employing either eccentric or coneccentric thread relief (Refs. 8,48) (see Figure 15).

The bearing surfaces of the tap lands should be as narrow as possible to minimize the work hardening of the tapped hole that occurs when these tap lands rub in the holes. All taps should have some back taper, around 0.001 inch per inch of length (Ref. 48).

The conventional two-flute, spiral-point, plug-style H2-pitch-diameter taps also can be modified by grinding away the threads behind the cutting edges down to the minor diameter, but leaving full-thread lands 0.015 inch wide backing up the cutting edges. Generally speaking, spiral-point taps featuring eccentric pitch-diameter relief with either full or interrupted threads have been the most successful (Refs. 29,48).

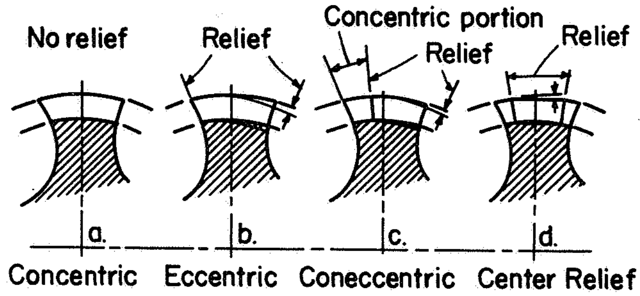


FIGURE 15. TYPES OF RELIEF USED ON TAPS

a. Concentric - No relief other than back taper.
b. Eccentric - Continuous relief from cutting edge to heel.
c. Coneccentric - Usually first third concentric, remainder eccentric relieved.
d. Center Relief - Concentric at cutting edge and heel, relieved at center.

The modifications described above reduce contact friction and binding, aid in the flow of cutting compounds, provide more clearance for chips, and compensate for the swelling that may be encountered, particularly when cutting these steels in the soft condition. They are effective measures for assuring good finish. Modifications of the kind described, however, may hinge on the assurance that the tap will maintain its alignment once it is started, and that it will hold its shape during cutting (Ref. 15).

Taps should be precision ground in a machine setup rather than by hand (Refs. 29,48). Extreme care should be used in grinding in order to provide equal chip loads on all cutting edges during tapping (Ref. 7). Stress relieving taps after grinding is also helpful.

Number of Flutes. Positive removal of chips is essential for obtaining a good finish. Attention also must be given to the amount of space available for free movement of chips to prevent clogging of flutes. A four-flute design on small taps is more liable to promote congestion than the two-fluted tap that allows more chip room (Ref. 15). The smaller number of flutes also assures more strength in the shank of small taps, which is an important factor on small holes (Refs. 7,15,33). Consequently, it is common practice to use the two-flute design on small taps, and then to use taps of three- and four-flute designs as taps sizes increase.

Two-fluted taps are usually used for 5/16-24 holes and smaller (Ref. 16), while three-fluted taps are best for 3/8 to 16 holes and greater, and for other tapping situations (Refs. 8,33,48,53). Four-fluted taps are acceptable for hole diameters greater than 5/8 inch (Ref. 33). The four-fluted tap also provides a lighter feed per tooth wherever that is important (Ref. 16).

Tap Design. Taps should have tool angles that encourage good chip flow, minimize seizure, and provide good shearing action. This usually means that

(1) A spiral-point angle large enough to allow chips to flow out of the hole ahead of the tap

(2) A relief angle large enough to prevent seizure but not so large as to cause jamming when backing out the tap

(3) Sufficient cutting rake to provide a good shearing action (Refs. 8,48)

(4) A chamfer to facilitate tap entry (Ref. 15).

The angle of chamfer with the center line of the tool should be around 9 degrees. Its length should extend between three and five threads for through holes in order to get under any work-hardened surface. A shorter chamfer results in high torque and possible tap breakage. An excessively long chamfer produces long, stringy chips that may jam the tap during backout operations. In any case, a tap will not cut properly unless its chamfer is ground evenly on each flute (Ref. 48). Where bottoming holes require complete threads close to the bottom of the hole, a series of two or three taps with successive shorter chamfers may be required. One investigator suggests five to ten chamfered threads on starting taps, four to five chamfered threads on intermediate taps, and one to two chamfered threads on finishing taps (Ref. 48).

Thread Engagement. The percent depth of thread in a tapped hole is an extremely important factor to both the designer and the tool engineer (Ref. 16). The thread engagement will depend on the material thickness, as shown in Table XVII, for conventional stainless steels (Ref. 15).

TABLE XVII. NORMAL THREAD ENGAGEMENT FOR CONVENTIONAL STAINLESS STEELS (REF. 15)

Material Thickness, in.	Percent Thread[a]
<1/2 the tap diameter	100
1/2 to 2 x tap diameter	75
>2 x tap diameter	50

(a) Avoid tapping over 75 percent thread in stainless steel-type alloys (Ref. 62).

A 70 to 80 percent thread is generally specified in aircraft design. However, because the shallower 60 percent thread is easier to machine, it would seem desirable for designers to make every effort to specify this value in aircraft and missile applications (Ref. 16). Thread strength tests show that any increase in thread height above 60 percent for the tapped member does not necessarily increase the static strength of a threaded fastener. In general the bolt will break at 55 percent engagement (Ref. 8). Standard tap-drill-selection tables in use for many years, based on a 75 percent thread engagement, were prepared on low-strength material such as brass. Modern high-strength alloys, however, possess adequate holding strength with a lower percentage of thread engagement (Ref. 8). This is accomplished by using larger tap-drill sizes than those recommended.

Tap Materials. High-speed steel taps (AISI M10) are usually used for tapping the nonstainless alloy steels and the various stainless steel alloys (Refs. 15,53). However, they cannot be used to tap D6a steel at hardnesses above 54 R_C (Ref. 54). At hardnesses between 52 and 54 R_C, the high-speed steel tap must be nitrided (Ref. 54). Cyaniding also proves beneficial by increasing the wear resistance of the cutting edges (Ref. 16).

Carbide taps are usually impractical (Refs. 7,31).

Setup Conditions. The tap should be mounted in a properly aligned holder to avoid breakage (Ref. 62). In addition, the shortest tap possible for the hole being tapped should be used for maximum tool rigidity (Refs. 7,29). Additional precautions in setups for tapping parallel those recommended for drilling. Lead-screw tapping is recommended since it is less dependent on the operator. The tapping head must be set for as short a stroke as possible. The use of a drill chuck to drive a tap is impractical (Ref. 33). Hand tapping is not recommended since it lacks the required rigidity and is extremely slow and difficult.

Tapping Speed. Tapping speeds should be limited to values between 5 and 30 fpm depending on the alloy and heat-treated condition. This is important because cutting torque increases extremely rapidly beyond a certain critical speed for each alloy (Ref. 53).

Size of Cut. The size of cut determines the incidence of tap seizure, and the size of cut is determined by the chamfer given the tap. The normal chamfer of five threads in a plug tap should produce smaller chips and minimize jamming the tap during the backing-out phase (Ref. 16).

Tapping Lubricants. The selection of tapping lubricants is important because of the susceptibility of taps to seizure. Highly active cutting fluids are recommended (Ref. 16). Highly chlorinated oils usually give good results. Another good lubricant is a heavy sulfurized mineral oil (Ref. 53). Mechanical filler materials such as molybdenum disulfide may be added to relieve persistent seizures. The chlorinated oils are sometimes mixed with inhibited trichlorethane (Ref. 54). Ordinary soluble oils are unsatisfactory for tapping because they lack the extreme-pressure properties needed to withstand the cutting pressures involved. The action of various cutting fluids during machining is explained on pages 23 to 25 inclusive.

Some fabricators recommend pretreating taps with colloidal molybdenum disulfide. The tap is dipped in a suspension of MoS_2 and white spirits, and then baked for 40 minutes at 200 C.

Additional Requirements. As in all tapping operations, regardless of material, the first step in the production of a threaded hole is to determine the optimum diameter of the hole to be tapped. This fixes the tap drill size or the size of the reamer if the latter is used.

Clean, round holes are essential for tapping (Ref. 48). Hence, as a first requirement, holes for tapping should have been produced by sharp drills operating under proper drilling conditions. Dull drills produce surface-hardened holes that will magnify tapping difficulties.

Sharp, clean taps must be used at low tapping speeds with recommended tapping compounds and under rigid tool-work setups.

Immediately before tapping a hole, the tap should be covered with a liberal amount of lithopone paste or white lead and lard oil (Ref. 16). If sulfurized oil is used, it should be forced on the tap throughout the tapping operation.

Taps should be inspected carefully after each use for possible smearing of the tap lands. Smear-type buildups may be hard to see, however, they can cause premature tap breakage and oversized holes. The workpiece also should be inspected for possible torn threads and dimensional discrepancies. It should be remembered that most tapping is done on parts that are 80 to 90 percent finished, therefore, scrap resulting from faulty tapping operations can be very costly.

Tapping is a slow procedure for most high-strength materials. In the case of the nonstainless alloy steels described in this report, practically all hole tapping should be done before final hardening. Hand tapping will bring threads to finish condition and size (Ref. 49).

Operating data for tapping all alloys are contained in Table XVIII. Tap designs are shown in Figure 16.

REAMING

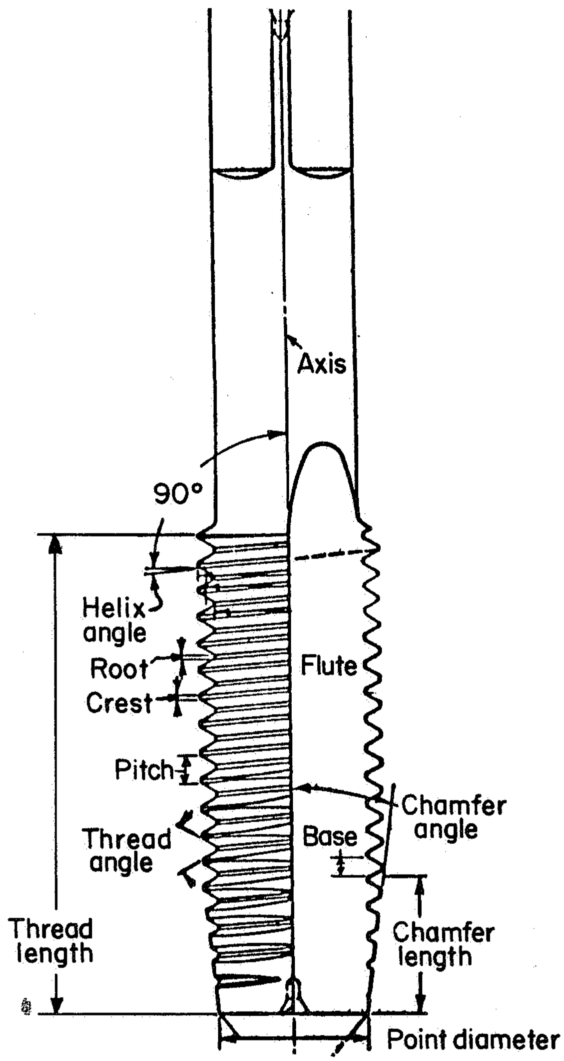
Introduction. Nonstainless alloy steels and stainless steels can be reamed successfully. Although adhesion of metal to the reamer can be a problem, particularly for the austenitic alloys, it must be prevented to avoid the production of oversized holes and poor finishes. Troublesome chatter may originate from a lack of rigidity, misalignment, the wrong tool geometry, and dull tools (Ref. 8).

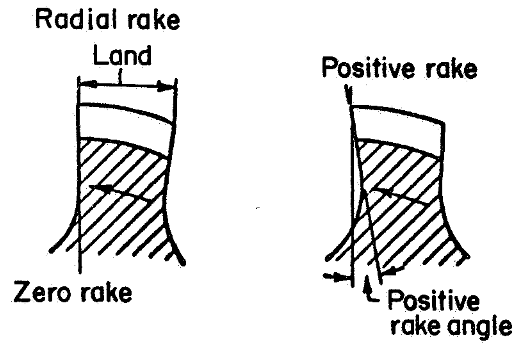
Types and Designs of Reamers. Fluted reamers are available as standard items. Spiral-fluted reamers can be identified as those usually possessing right-hand cuts, along with positive axial (helix) and radial rake angles (Ref. 8). Both types of reamers afford a smoother cutting action, better chip disposal, and are less apt to dig in or chatter than straight-fluted reamers, although the straight-fluted styles are usually preferred when extreme accuracy is required (Ref. 15). Some people recommend a left-hand spiral reamer for a right-hand cut. Although right-hand spiraling of the flutes helps the tool to cut more freely in this situation, it also tends to make the reamer feed into the work too rapidly (Ref. 77).

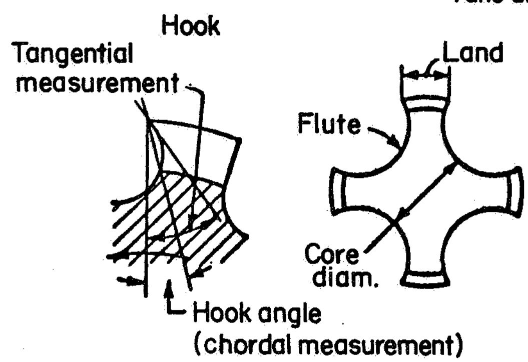
TABLE XVIII. TAPPING DATA FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS(a)

Alloy Group	Alloy Group Representatives	Alloy Condition(b)	Tap Designation: HSS Grade(c)	Tap Designation: Tap Style(d)	Tap Designation: Tap Percent Thread	Cutting Speed, fpm	Cutting Fluid(e)
	Nonstainless Alloy Steels						
	Cr-Mo low-alloy steels						
A1	A-4130	Ann 150-230 Bhn	M2	A	70	30	IIa, IIIa, IIIb, IV
	A-4130	HT 315-370 Bhn	M2	B	60	15	IIa, IIIa, IIIb, IV
	Cr-Ni-Mo low-alloy steels						
C1	A-4340	Ann 150-230 Bhn	M2	A	70	30	IIa, IIIa, IIIb, IV
	A-4340	HT 315-370 Bhn	M2	B	60	15	IIa, IIIa, IIIb, IV
	A-4340	HT 510-560 Bhn	M10 (cyanided) M2	B	60	5	IIIc
D2	H-11	Ann 160-220 Bhn	M2	A	70	20	IIa, IIIa, IIb, IV
	H-11	HT 340-370 Bhn	M2	B	60	15	IIa, IIIa, IIIb, IV
	H-11	HT 515-560 Bhn	M10 (cyanided) M2	B	60	5	IIIc
	Maraging steels						
D3	18 Ni Co Mo	HR HR - Ann	M10 (nitrided)	A	70-75	15	
		Mar.	M10 (nitrided)	B, C, D	50-55	7	
	Cr-Ni-Mo steel						
E1	D6a	HT 52 R_C	M10 (nitrided)	C	65	5	IIIc
	Stainless Steel Alloys						
	Straight-chromium grades						
B4	405	Ann 150-200 Bhn	M2	A	< 75	10-25	IIb, IIIa, IIIb, IV
C4	442	Ann 150-200 Bhn	M2	A	< 75	10-25	IIb, IIIa, IIIb, IV
B5	410	Ann 160-220 Bhn	M2	A	< 75	10-25	IIb, IIIa, IIIb, IV
	410	HT 300-350 Bhn	M10 (nitrided) M2	B2	60-70	15-20	IIb, IIIa, IIIb, IIIc, IV
D5	440 B	Ann 215-260 Bhn	M2	A	< 75	20	IIb, IIIa, IIIb, IV
	440 B	HT 300-350 Bhn	M2	B2	< 75	15	IIb, IIIa, IIIb, IV
	Precipitation-hardenable grades						
D6	17-7 PH	Ann 160-180 Bhn	M2, M10	A		20	IIa, IIIa, IIIb, IV
	17-7 PH	HT 380-440 Bhn	M2, M10	B2	75	5-10	IIa, IIIa, IIIb, IV
	Chromium-nickel grades						
D7	347	Ann 160-220 Bhn	M2	A	65	10-25	IIb, IIIa, IIIb, IV
	Austenitic Stainless Steels Superalloys						
E9	A286	STA 320 Bhn	M10	A	75	30	IIIb

(a) From References: 15, 16, 33, 49, 63.
(b) Ann = annealed; HT = heat treated; HR = hot rolled; Mar. = maraged; STA = solution treated and aged.
(c) AISI designations shown.
(d) A = spiral pointed or spiral fluted
B = taper
C = plug
D = bottoming.
(e) See page 53 for specific types.







Tap Elements	Tap-Design Code 1	2	3
Rake angle, degrees	8 to 12	12 or	--
Hook angle, degrees	--	10 to 15	15 to 20
Relief angle, degrees	5	5	5
	Straight-Fluted Tap	Chamfer Angle, degrees	Chamfer Length, threads
Chamfer data for all designs	Taper (B)	4 to 5	8 to 10
	Plug (C)	9 to 10	3-1/2 to 5
	Bottom (D)	30 to 35	1 to 2

FIGURE 16. NOMENCLATURE AND TYPICAL DESIGNS FOR TAPS (STAINLESS STEEL ALLOYS)

The use of end-cutting, straight-fluted right-hand-cut reamers is recommended for maraging steels except when reaming a tapered hole, or when reaming under conditions where the tool tends to jump ahead as a result of uneven feed. Under these conditions reamers with the hand of spiral opposite to the hand of cut, such as left-hand spiral, right-hand cut are recommended. Tapered-shank reamers are preferred since they give less runout than the straight-shank reamers do (Ref. 33).

Solid reamers* are usually the better choice in the smaller sizes since the possibility of error and deflection is reduced. However, they may be uneconomical in large sizes because of their higher initial costs. Nevertheless, some companies use them in the larger sizes and then regrind them to the next lower size if the die-size range permits (Ref. 78).

Reamers for the stainless steels should be ordered with narrow land widths to reduce rubbing, thus minimizing work hardening of the work material. Reamers with margins about 0.010 inch wide produce acceptable holes. Scoring is a problem with wider margins, and excessive chatter is likely to occur when margins are less than 0.005 inch.

All reamers should be as short as possible, not only for maximum rigidity, but also to lessen the possibility of reaming bell-mouthed or tapered holes. In addition, the chamfer must be concentric with all flutes of the reamer.

Tool Geometry. The conventional reamer has three basic tool angles: a chamfer angle, a rake angle, and a relief angle. The relief angle is very influential and should exceed 5 degrees, to minimize smearing. On the other hand, relief angles in excess of 10 degrees cause vibration and chatter marks on the surface of reamed holes. For deep holes, or when working austenitic stainless steels, a rake angle of 5 to 8 degrees will reduce the power required and will produce a better chip condition and surface finish.

Tool Materials. AISI M2 and M10 high-speed steel reamers can be used on hardened alloy steels and stainless steel alloys. Sometimes a surface treatment will improve the resistance of reamers to wear and abrasion produced by these materials.

*Other reamers sometimes used include the shell- , adjustable- , and inserted-blade types (Ref. 78).

Carbide-tipped reamers also can be used and operate at somewhat higher speeds and have much better tool life. Type C-50 and C-2 carbide tools are recommended for hot-worked or annealed maraging steel and Type C-2 or Type C-70 are recommended for reaming maraged material (Ref. 33).

Setup Conditions. There seems to be a rather narrow range of reaming conditions that will give optimum results. Consequently, the basic precautions for machining work-hardening alloys should be heeded. These include adequate rigidity of setup, sharp tools, and a positive feed to prevent riding without cutting. Chatter can be eliminated by altering tool design, size of cut, and cutting speed. Honed reamers produce smoother surfaces and last longer between grinds (Ref. 8).

A problem in machine reaming can occur if the axis of the spindle is not in exact alignment with the axis of the reamer. Causes for misalignment may originate from wear in the ways, wear or dirt in the sleeve or tool clamp, or poor leveling of the machine. These shortcomings are indicated when a rigidly mounted reamer produces poor finishes and oversized or eccentric holes, especially noticeable at the start of the reaming operation (Ref. 77).

To ream precisely and to minimize bell-mouth holes, guide bushings are recommended. Where reamers must guide themselves into the hole, a parallel floating holder to compensate for any parallel or angular misalignment is suggested. Smooth, straight holes are required for reaming to high-dimensional accuracy and surface finish (Refs. 15,33,77,78).

Cutting Speed. Recommended speeds vary among different materials and will depend on the need for dimensional tolerances or smooth finishes, or perhaps both. Where tolerance of the hole is the main factor, higher speeds can be used. Where smooth finishes are required, lower speeds are recommended. High-speed steel reamers operate in these high-strength materials within a range of 15 to 55 fpm depending on the alloy and heat-treated condition. Carbide reamers operate in the higher speed range of 25 to 160 fpm.

Feed. Feeds are based on the type of material, depth of cut, finish required, and design of reamer being used (Ref. 78). Small feeds are usually required to produce acceptable holes, and may range between 0.002 and 0.020 ipr depending on the reamer diameter and the alloy (Refs. 8,63). Too low a feed will result in chatter, glazing, and excessive wear. Conversely, an excessive feed rate reduces dimensional accuracy, impairs concentricity, and adversely affects surface finish.

Depth of Cut. A continuous cutting action is necessary in reaming; otherwise, burnishing, or work hardening of the work surface may result. Reamer life is also shortened when insufficient stock is removed. If the drill size is too close to the reamer size or if it drills oversize, the reamer will not have enough bite. Thus, the reamer may wedge rather than cut, resulting in excessive wear or even breakage (Ref. 78).

As the diameter of the hole increases, the amount allowed for reaming also should be increased. This is illustrated in Table XIX for materials like D6a, the maraging steels, the stainless steels, and the stainless steel superalloys (Refs. 33,78).

TABLE XIX. ALLOWANCES ON DIAMETERS OF HOLES FOR HIGH-SPEED STEEL REAMERS

Alloy				Allowance on Diameter, inch, for Diameter of Drilled Holes,			
				Diameter of Holes, inch			
Group	Group Representative	Alloy Condition	Type Operation	1/4	1/2	1	1-1/2
	Maraging steels						
D3	18Ni-Co-Mo	Hot rolled,	Semifinish,	0.015	0.015	--	0.030
		annealed	finish	0.005	0.005	--	0.015
		Maraged	Semifinish,	--	--	--	--
			finish	--	--	--	--
	Cr-Ni-Mo						
E1	D6a	Heat treated (56 R_C)	--	0.010	--	--	--
	Stainless steels All grades						
D5		--	--	0.006	--	0.016	--
D6		--	--	--	--	--	--
D7		--	--	--	--	--	--
	Stainless steel alloys						
D8		--	--	0.010	0.015	--	0.025
D9		--	--	--	--	--	--
E8		--	--	--	--	--	--
E9		--	--	--	--	--	--

Cutting Fluids. The most effective fluids for reaming high-strength steels, and stainless steel alloys are the chemically active types including the sulfochlorinated oils, the highly chlorinated oils, and the highly sulfurized oils. An ample supply of these fluids is required since the long cutting edges of a reamer generate a considerable amount of heat (Refs. 79,80).

Additional Requirements. Reamers should be ground in fixtures or on tool and cutter grinders. The quality of finish produced by reaming depends to a great extent on the proper width of lands and on the finish of the cutting edges. A polished finish on a reamer will produce a better finish on the part. Coarse grinding marks on the reamer will transfer their patterns to the finished hole. Furthermore, stoning the edges of reamers after grinding materially lengthens the life of the tool (Ref. 33).

Reamers should be handled and stored carefully. This usually means storage in individual racks or partitioned boxes. If the reamer is dropped on hard surfaces or hit by other tools, the unprotected cutting edges may be nicked. When not in use, reamers should be protected with a complete coating of oil to prevent rusting. A small spot on the cutting edge will start a pit or a nick. A deep nick can spoil a reamer (Ref. 77).

Cutting speeds and feeds for nonstainless alloy steels and stainless steel alloys are shown in Table XX. Reamer designs for these data are shown in Figure 17.

BROACHING

Introduction. Broaching is a machining operation that shaves metal from slots or holes using multiple-stepped cutting edges on a tool that is either pulled or pushed through the work. Cylindrical or square holes and slots can be finished by broaching tools designed for the particular cut or opening involved.

Hardened steels and stainless steel alloys can be broached under the general setup conditions of rigidity, positive feed, etc., required for turning, milling, and other machining operations. Because of the interrupted nature of cutting, welding of metal to the cutting tool followed by edge chipping (as in milling) can be quite troublesome. Alloys in Groups D6 and E9 categories can be broached more cleanly in the aged condition.

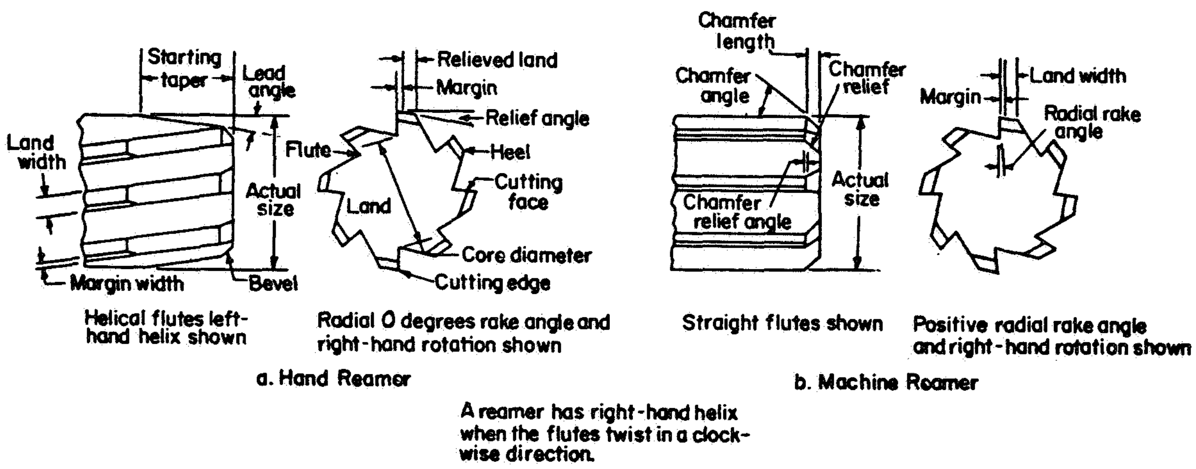
TABLE XX. REAMING DATA FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS[a]

Alloy								Feed for Reamer Diameter Shown, ipr					
								Nominal Reamer Diameter, inch					
Group	Group Representative	Alloy Condition[b]	Tool Material	Grade[c]	Design[d]	Cutting Speed[e], fpm	Cutting Fluid[f]	1/8	1/4	1/2	1	1-1/2	2
						Nonstainless Alloy Steels							
	Cr-Mo low-alloy steels												
A1	A-4130	Ann (150-230 Bhn)	High-speed steel	T1, M1	C	45	I, IIa	0.003	0.004	0.008	0.012	0.015	0.020
			Carbide	C-2	C	160	I, IIa	0.003	0.004	0.008	0.012	0.015	0.020
E1	A-4130	HT (350 Bhn)	High-speed steel	T5, M2	D	25	IIa, IIIa, IV	0.002	0.003	0.005	0.009	0.012	0.015
			Carbide	C-2	D	65	IIa, IIIa, IV	0.002	0.003	0.005	0.009	0.012	0.015
	Cr-Ni-Mo low-alloy steels												
C1	A-4340	Ann (150-230 Bhn)	High-speed steel	T1, M1	C	45	I, IIa	0.003	0.004	0.008	0.012	0.015	0.020
			Carbide	C-2	C	160	I, IIa	0.003	0.004	0.008	0.012	0.015	0.020
	A-4340	HT (240-310 Bhn)	High-speed steel	T5, M2	C	30	I, IIa	0.002	0.004	0.008	0.012	0.015	0.020
			Carbide	C-2	C	125	I, IIa	0.003	0.004	0.008	0.012	0.015	0.020
F1	A-4340	HT (315-370 Bhn)	High-speed steel	T5, M2	D	25	IIa, IIIa, IV	0.002	0.003	0.005	0.009	0.012	0.015
			Carbide	C-2	D	65	IIa, IIIa, IV	0.002	0.003	0.005	0.009	0.012	0.015
	5Cr-Mo-V die steels												
D2	H-11	Ann (160-220 Bhn)	High-speed steel	T1, M1	C	30	I, IIa	0.003	0.005	0.008	0.012	0.015	0.020
			Carbide	C-2	C	120	I, IIa	0.003	0.005	0.008	0.012	0.015	0.020
F2	H-11	HT (340-375 Bhn)	High-speed steel	T15	D	20	IIa, IIIa, IV	0.002	0.003	0.004	0.007	0.010	0.012
			Carbide	C-2	D	60	IIa, IIIa, IV	0.002	0.003	0.004	0.007	0.010	0.012
G2	H-11	HT (515-560 Bhn)	High-speed steel	--	--	--	--	--	--	--	--	--	--
			Carbide	C-2	D	20	IIa, IIIa, IV	0.002	0.003	0.004	0.006	0.008	0.010
	Maraging steels												
D3	18Ni-Co-Mo	Ann	High-speed steel		B	40-55	I, IIa	0.002	0.002	0.003	0.008	--	--
			Carbide		B	70-100	I, IIa	--	--	--	--	--	--
G1		Maraged	High-speed steel		B	15-25	IIa, IIIa, IV	--	--	--	--	--	--
			Carbide		B	25-50	IIa, IIIa, IV	--	--	--	--	--	--
	Cr-Ni-Mo Steels												
G2	D6a	HT (56 RC)	Carbide-tipped	C-2	E	65	IIIb	--	0.002	--	--	--	--

TABLE XX. (Continued)

Group	Alloy Group Representative	Alloy Condition(b)	Tool Material	Grade(c)	Design(d)	Cutting Speed(e), fpm	Cutting Fluid(f)	Feed for Reamer Diameter Shown, ipr — Nominal Reamer Diameter, inch: 1/8	1/4	1/2	1	1-1/2	2
							Stainless Steel Alloys						
	Straight-chromium grades												
B4	405	Ann (150-200 Bhn)	High-speed steel	T1, M1	A	40	I, IIa	0.004	0.007	0.010	0.016	0.020	0.025
			Carbide	C-2	C	140	I, IIa	0.004	0.007	0.010	0.016	0.020	0.025
B5	410	Ann (160-220 Bhn)	High-speed steel	T1, M1	A	45	I, IIa	0.003	0.005	0.010	0.016	0.020	0.025
			Carbide	C-2	C	140	I, IIa	0.003	0.005	0.010	0.016	0.020	0.025
F5	410	HT (300-350 Bhn)	High-speed steel	T5, M2	D	20	IIa, IIIa, IV	0.002	0.005	0.010	0.016	0.020	0.025
			Carbide	C-2	D	80	IIa, IIIa, IV	0.002	0.005	0.010	0.016	0.020	0.025
D5	440B	Ann (215-260 Bhn)	High-speed steel	T5, M2	A	25	I, IIa	0.002	0.005	0.010	0.016	0.020	0.025
			Carbide	C-2	C	100	I, IIa	0.002	0.005	0.010	0.016	0.020	0.025
G5	440B	HT (375-440 Bhn)	High-speed steel	T5, M2	D	15	IIa, IIIa, IV	0.001	0.003	0.007	0.010	0.012	0.015
			Carbide	C-2	D	60	IIa, IIIa, IV	0.001	0.003	0.007	0.010	0.012	0.015
	Precipitation-hardenable grades												
D6	17-7 PH	Ann (160-180 Bhn)	High-speed steel	T5, M2	C	25	I, IIa	0.003	0.005	0.010	0.016	0.020	0.025
			Carbide	C-2	C	100	I, IIa	0.003	0.005	0.010	0.016	0.020	0.025
F6	17-7 PH	HT (380-440 Bhn)	High-speed steel	T15	D	15	IIa, IIIa, IV	0.002	0.003	0.004	0.007	0.010	0.012
			Carbide	C-2	D	60	IIa, IIIa, IV	0.002	0.003	0.004	0.007	0.010	0.012
	Chromium-nickel grades												
D7	347	Ann (160-220 Bhn)	High-speed steel	T1, M1	A	30	I, IIa	0.002	0.005	0.010	0.016	0.020	0.025
			Carbide	C-2	C	120	I, IIa	0.003	0.005	0.010	0.016	0.020	0.025
							Austenitic Stainless Steel Superalloys						
	Nonheat-treatable grades												
D8	19-9DL	ST (180-220 Bhn)	High-speed steel	T15	C	15	IIa, IIIa, IV	0.002	0.003	0.005	0.008	0.010	0.010
			Carbide	C-2	C	65	IIa, IIIa, IV	0.002	0.003	0.005	0.008	0.010	0.015
E8	Timken 16-25-6	ST	High-speed steel		C	20	IIa, IIIa, IV	0.002	0.003	0.005	0.008	0.010	0.010
			Carbide		C	70	IIa, IIIa, IV	0.002	0.003	0.005	0.008	0.010	0.010
	Age-hardenable grades												
E9	A-286	STA (320 Bhn)	High-speed steel		C	20	IIa, IIIa, IV	0.002	0.003	0.005	0.008	0.010	0.010
			Carbide		D	70		0.002	0.003	0.005	0.008	0.010	0.010

(a) From References 15, 33, 54, 63, 77-80.
(b) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.
(c) AISI designations for high-speed steels (see page 18); CISC designations for carbides (see page 15).
(d) See Figure 17 for tool angles.
(e) For quality surface finishes on stainless steels, speeds of 20 to 40 fpm are recommended for high-speed steel reamers. If hole size is more important, speeds between 40 and 120 fpm are sometimes used (Refs. 78, 79).
(f) See page 25 for specific types.



Reamer Information	A Stainless Steels	B Maraging Steels Diameter of Hole, inch Up to 1/2	 1/2 to 1	 1-1/2 to 2	C Cr-Mo Steels Cr-Ni-Mo Steels H-11 Steels Stainless Steels pH Stainless Steels 180/250 Bhn	D Cr-Mo Steels Cr-Ni-Mo Steels H-11 Steels 350/500 Bhn	E D6a Steel 56 R_C
		High-Speed Steel Reamers			Carbide-Tipped Reamers		
Tool angles, degrees							
Helix	7	--	--	--	5 to 8	0	0
Radial rake	3 to 5	0 to 5(a)	0 to 5(a)	0 to 5(a)	7 to 10	5 to 7	--
Relief	6 to 8	10 to 15	8 to 10	6 to 8	--	--	--
Primary chamfer	30 to 35	45	45	45	--	--	45
Secondary chamfer (lead)	--	--	--	--	2	0	--
Chamfer relief	--	12	8 to 12	7 to 9	--	--	10
Chamfer secondary relief	--	(c)	(c)	(c)	--	--	--
Margin data							
Margin width, inch	--	0.004 to 0.010	0.010 to 0.015	0.015 to 0.020	0.005 to 0.010(d)	0.002 to 0.005	--

(a) Use 0 degree on carbide-tipped reamers and spiral-fluted reamers.
(b) Reduce rake angles to 0 to 45 degrees for the 500 Bhn steels.
(c) Apply sufficient secondary relief to carbide reamers to prevent tool drag.
(d) Reduce margin to 0.002 to 0.005 inch for 250 Bhn Cr-Mo, Cr-Ni-Mo, and H-11 steels.

FIGURE 17. REAMER DESIGN FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS

Type of Broaches.

Design. Tool design has noticeable effects on broaching performance. The relief angle, rake angle, and the rise per tooth seem to be the more important elements. Teeth should have a positive rake so that the chips will curl freely into the gullets. The gullet size should be large enough to accommodate the chips formed during the operation.

Broaches are sometimes made slightly oversize (0.0005 inch) to compensate for the slight springback that will occur when the cut is completed.

The alloys covered in this report usually require relief angles between 1/2 to 2 degrees, values normally used in broaching other materials. If the relief angle is too small, metal pickup on the land relief surface can seriously affect the quality of the broached surface.

A rake or hook angle of 20 degrees is normally recommended for broaching conventional materials. For stainless steel-type alloys, however, smaller angles down to 8 degrees, depending on the alloy, will improve broaching performance to a marked degree. The smaller rake angles provide greater support for the cutting edge, and improve heat transfer from the cutting zone. The maximum rake is about 20 degrees for Group E9 alloys, 18 degrees for Groups B4 and D7 alloys, and 15 degrees for Groups A1, B5, C1, and D6 alloys. Increases beyond these values invite tool failure.

The normal recommendation for the rise per tooth in broaching steel is 0.0005 to 0.003 inch. The annealed stainless steels and alloy steels, however, should be broached at 0.001 to 0.005 inch per tooth. The lower value of this range should provide smaller cutting forces and better surface finishes. The hardened steels require lower chip loads (0.002 ipt).

Tool Materials. Any type of high-speed steel should work reasonably well as a broaching tool. The standard AISI types T1, T4, M2, M4, and M10 should give good performance in the speed ranges recommended.

Setup Conditions. Rigidity of work and tool is necessary to avoid a consecutive series of flat surfaces on the workpiece. Surface broaching requires much greater rigidity in fixturing than does hole broaching. Hole broaching provides an inherent rigidity derived from the cutter motion against the work-holding device or fixture.

The broach should not ride on the work without cutting.

Cutting Speed. Some alloys have shown a marked sensitivity to cutting speed. Thus, it appears reasonable to recommend low, constant speeds for this type of operation to minimize cutting temperature and tool wear.

Cutting speeds should be restricted to the range of 10 to 25 fpm for Groups A, B, C, and D alloys, and around 8 fpm for the stainless steel superalloys (Group E).

Depth of Cut. The depth of cut is governed by the "rise per tooth" of the broach. A rise per tooth in the range of 0.002 to 0.005 inch has been used successfully when a +5-degree relief is employed. If a 2-degree relief is used, the rise should be reduced to 0.0015 ipt for stainless steel superalloys and 0.002 ipt for the Groups A, B, C, and D alloys.

Cutting Fluid. A generous supply of cutting fluid must flow to the cutting edges of the teeth. It should be free flowing and of sufficient body to provide good lubricity. Sulfurized oils seem to give the best results since they minimize friction, improve surface finish, and reduce wear rates. A prior application of an oil with a high-strength film to the surface to be broached will greatly minimize the chip-welding tendency and prolong tool life between grinds.

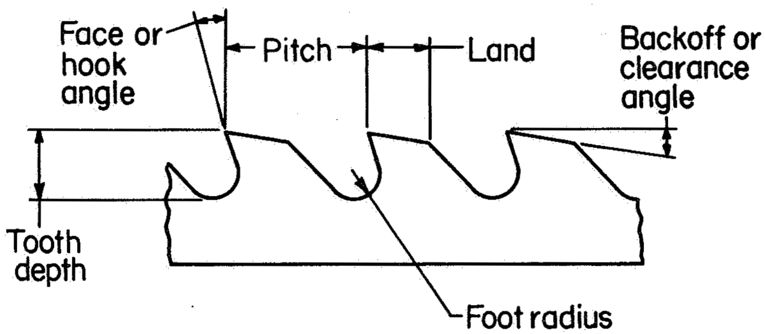
Additional Requirements. Chips should be removed from broaching tools before each pass. Any excessive wear and smearing along the cutting edge should be corrected at that time. Tools should be kept sharp to reduce the tendency of smearing (of the land), which eventually leads to tool failure. Tools must be reground at the first sign of dulling. Teeth should be polished or honed to remove all peaks and irregularities left by the grinding wheel. The gullets should be polished for better chip flow.

Operating data for broaching these alloys are shown in Table XXI. Figure 19 illustrates the broaching designs.

TABLE XXI. BROACHING DATA FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS[a]

Alloy Group	Alloy Group Representative	Alloy Condition[b]	High-Speed Steel Tool Grade[c]	High-Speed Steel Tool Design[d]	Operating Data: Chip Load, ipt	Operating Data: Cutting Speed, fpm	Operating Data: Cutting Fluid[e]
	Nonstainless Alloy Steels						
	Cr-Mo low-alloy steels						
A1	4130	Ann (150-230 Bhn)	T1, M3	A1	0.005	20	I, IIa, IIIa, IV
E1	4130	HT (315-370 Bhn)	T5, T15	--	0.002	10	IIa, IIIa, IV
	17-22AS	HT (350 Bhn)	--	--	--	--	--
	Cr-Ni-Mo low-alloy steels						
C1	A-4340	Ann (150-230 Bhn)	T1, M3	A1	0.005	20	I, IIa, IIIa, IV
F1	A-4340	HT (315-370 Bhn)	T5, T15	--	0.002	10	IIa, IIIa, IV
	5Cr-Mo-V die steels						
D2	H-11	Ann (160-220 Bhn)	T1, M3	D2	0.004	20	I, IIa, IIIa, IV
F2	H-11	HT (340-375)	T5, T15	--	0.002	10	IIa, IIIa, IV
G2	H-11	HT (515-560 Bhn)	--	--	--	--	--
	Stainless Steel Alloys						
	Straight-chromium grades						
B4	405	Ann (150-200 Bhn)	T5, M3	B4	0.001-0.005	10-20	I, IIa, IIIa, IV
B5	410	Ann (160-220 Bhn)	T5, M3	B5	0.001-0.005	10-25	I, IIa, IIIa, IV
F5	410	HT (300-350 Bhn)	T15	--	0.002	10	IIa, IIIa, IV
		HT (350-375 Bhn)	T15	--	0.0015	5	IIa, IIIa, IV
D5	440B	Ann (215-260 Bhn)	T5, M3	B5	0.003	15	I, IIa, IIIa, IV
G5	440B	HT (300-350 Bhn)	T15	--	0.002	10	IIa, IIIa, IV
	Precipitation-hardenable grades						
D6	17-7PH	Ann (160-180 Bhn)	M2, T15	D6	0.002	10	I, IIa, IIIa, IV
F6	17-7PH	HT (380-440 Bhn)	--	--	--	--	--
	Chromium-nickel grades						
D7	347	Ann (160-220 Bhn)	T5, M3	D7	0.001-0.005	10-15	I, IIa, IIIa, IV
	Austenitic Stainless Steel Superalloys						
	Nonheat-treatable grades						
D8	19-9DL	ST (180-220 Bhn)	T15	E9	0.002	8	IIa, IIIa, IV
	Age-hardenable grades						
E9	A-286	ST (180-220 Bhn)	T15	E9	0.002	8	IIa, IIIa, IV
	A-286	STA (280-320 Bhn)	T15		0.002	10	IIa, IIIa, IV

(a) From References 15, 56, 63, 77-80.
(b) Ann = annealed; HT = heat treated; ST = solution treated; STA = solution treated and aged.
(c) AISI designations are used for high-speed steels.
(d) See Figure 18 for tool angles involved.
(e) See page 25 for specific types.



Material	Alloy Steels: Cr-Mo Cr-Ni-Mo	Die Steel: 5Cr-Mo-V	Stainless Steels Ferretic	Martensitic	Precipitation Hardenable	Austenitic	Stainless Steel Superalloys
Tool-geometry code	A1	D2	B4	B5	D6	D7	E9
Rake or hook angle, degrees	8 to 15	8 to 12	12 to 18	10 to 15	10 to 15	12 to 18	15 to 20
Relief angle, degrees	1 to 3	1 to 2	2 to 3(a)	1 to 2(a)	2	1/2 to 2(a)	2 to 3
Rise per tooth, inch	See page 95.						

(a) Relief angles up to 5 degrees are sometimes suggested.

FIGURE 18. BROACH DESIGNS FOR USE ON NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS

PRECISION GRINDING

Introduction. Methods of grinding nonstainless alloy steels and stainless steel alloys do not differ greatly from the practices followed for ordinary steel. However, grinding these highly alloyed steels improperly can induce unusually high cutting temperatures and chemical reactions between the workpiece and the abrasive. This causes dulling of wheels (or belts) by "capping" of the grains with welded-on metal or by glazing and burnishing of the surface being ground. These troubles can be avoided by following three basic precautions:

(1) Choosing an abrasive wheel (or belt) that allows controlled progressive intergranular chipping as flat spots develop on the grits

(2) Using appropriate speeds to minimize grinding temperatures and welding reactions

(3) Utilizing a chemically active grinding fluid that will develop a low-shear-strength film between chip and grit.

Low grinding temperatures also minimize the residual stresses in a finish-ground part.

Stainless steel alloys can be ground at about the same rate as the hardened die steels. Moderately light cuts are recommended, and periodic dressings are required to keep the wheel in proper condition. Excessive wheel loading leads to poor grinding action and causes poor surface finish, high residual tensile stresses, and low grinding ratios. Grinding ratios involve the volume (cu in.) of metal removed to the volume of grinding wheel removed by wear during grinding. Low ratios mean poor wheel life. Wear ratios are analogous to tool life in machining where cubic inches of metal removed are related to flank wear.

If a choice of finish-machining methods exists in a potential grinding situation, serious considerations are usually given to turning, boring, or milling operations rather than grinding. These operations require less time than grinding and give excellent surface finishes. Nevertheless, when only a small amount of material is to be removed, the finishing operation can be done on a grinding machine using a rough and then a finish grind.

Machine-Tool Requirements. There are many high-quality grinders available today. Most of the existing machines can be set for the required light downfeeds, but may have no means of adjusting the spindle speed. Furthermore, not many production grinders are equipped with automatic wheel-wear compensation. Such devices improve dimensional control, especially when softer wheels are used (Ref. 16).

Some existing grinders are being modernized to provide wheel speeds needed for high-strength alloys. Devices for automatic gaging and sizing, wheel dressing, and wheel compensation are being added to the ultraprecision grinders. Increased rigidity in the spindle system together with automatic wheel balancing are highly recommended features for grinding the high-strength, high-temperature-resistant materials (Ref. 16).

Grinding Wheels. Properly operated grinding wheels should wear by attrition and fracture of the bond.

Normal attrition involves, as a continuous process, a gradual smoothing of the individual abrasive grains during cutting. It is followed by intergranular fractures that are supposed to provide successively new sharp-cutting surfaces until the entire grain leaves the wheel.

If the grains break away too slowly, the workpiece material is deposited on and in between the abrasive grains. As wheel loading continues, and the wheel becomes smoother, the grinding rate decreases. Glazing is similar, except that the tips of the grain wear smooth and become shiny as a result of friction. Smooth wheels resulting from either cause burnish the workpiece and may result in burning, high residual stresses, and cracked surfaces.

If the grains break away too rapidly, either during grinding, or by frequent wheel dressing, wheel wear is excessive.

Generally speaking, medium-grade grinding wheels offer the best compromise between life and surface stresses. Hard wheels are likely to become embedded with particles of metal that dull the wheel rapidly and necessitate frequent wheel dressing. Furthermore, some of the abrasive grains of hard wheels may become embedded in the ground surface of the workpiece. These grains may cause scratching of a contacting part during service.

TABLE XXII. CHART OF MARKINGS ON GRINDING WHEELS

Abrasive Symbols[a] Silicon Carbide	Abrasive Symbols[a] Aluminum Oxide	Grit Size Coarse	Grit Size Medium	Grit Size Fine	Grit Size Very Fine	Grain Combination		Wheel Grade Soft	Wheel Grade Medium	Wheel Grade Hard	Structure Dense	Structure Medium	Structure Open	Bond Form[b]	Bond Type Manufacturer's Symbols
5C	A	10						A			0			V	Modification bond[c]
6C	2A	12	36	90	240	1	coarse	B			1	5	9	R	
CA	97A	14	46	100	280	2		C			2	6	10	B	See manufacturer's brochures
C2A	4A	16	54	120	320	3		D	I		3	7	11	E	
C4A	9A	20	60	150	400	4		E	J		4	8	12	M	
7C		24	70	180	500	5		F	K				13	S	
		30	80	220	600	6		G	L	Q			14		
						7	fine	H	M	R			15		
									N	S			16		
									O	T					
									P	U					
										V					
										W					
										X					
										Y					
										Z					
A typical[d] marking sequence	4A	46				1	-	J			8	VL			

(a) Cincinnati Milling Machine Company nomenclature:

5C - green silicon carbide
6C - black silicon carbide
CA, C2A, C4A - mixed aluminum oxide and silicon carbide
7C - mixed silicon carbide

A - tough aluminum oxide
2A - semifriable
97A - friable mixture
4A - special friable
9A - very friable (white).

(b) V - vitrified
R - rubber
B - resinoid
E - shellac
M - metal
S - silicate.

(c) Some manufacturers also add a number designating whether the wheel grade is either exact, 1/3 softer, or 1/3 harder than the better grade indicated (L in the example shown).

(d) The sequence shown represents a grinding wheel used on A-4340 steel heat treated to 52 R_C.

Grinding wheels are available in various combinations of grit sizes, wheel hardnesses, and bond materials. These attributes influence metal-removal rates and wear for specific grinding conditions. Table XXII shows the wide choices available and indicates the makeup of a typical wheel used for grinding the various steels covered in this report.

Abrasives. The choice of a silicon carbide or aluminum oxide wheel depends on the grinding application.

Silicon carbide wheels are usually used for centerless and cylindrical grinding. On the other hand, aluminum oxide wheels are preferred for surface grinding because they are used at somewhat lower speeds. The optimum speed for silicon carbide wheels is much higher than for aluminum oxide wheels. In fact, if a wheel must be operated beyond 6000 fpm because of limited equipment availability, silicon carbide wheels should give better results than aluminum oxide wheels.

Special-friable aluminum oxide wheels are satisfactory for the steels and stainless steels covered in this report. Table XXIII lists some manufacturers' designations of these oxides. However, grinding wheels from different suppliers may be comparable but not necessarily identical.

TABLE XXIII. TYPES OF ALUMINUM OXIDE ABRASIVES USED FOR GRINDING VARIOUS STEELS

Manufacturer	Type of Abrasive Special-Friable Aluminum Oxide
Norton	32A
Cincinnati	4A
Carborundum	--
Bay State	3A - 8A
Chicago	52A
Desanno	7A
Macklin	26A
Simonds	7A
Sterling	HA

Grit Size. The size of the abrasive grains influences the efficiency of grinding by affecting the rate of intergranular fracturing and the supply of fresh cutting edges. Smaller grains tend to leave the wheel prematurely, resulting in faster wear. Larger grains dull excessively before leaving the wheel.

The optimum grit size for aluminum oxide wheels seems to be 46 when grinding the steels covered in this report.

Wheel Hardness. The material used to bond the abrasive grits determines the wheel hardness. It is usually desirable to use the hardest wheel that will not result in burning, or smearing of hard alloys, or chatter on softer alloys.

For this reason, the medium grades I to K seem to be suitable for the various steels and stainless steel alloys, although softer grades like H usually result in lower residual stresses in ground surfaces than harder grades.

Type of Bond. Vitrified bonds seem to give the best performance, possibly because they are more porous. As such, they permit better swarf (chip) clearances and lower grinding temperatures.

Setup Conditions. The following recommendations are suggested in order to provide the good grinding environment needed for the hardened steels and various stainless steel alloys:

(1) High-quality grinders with variable table and spindle speeds

(2) Rigid setup of work and wheel to avoid vibrations that cause surface damage

(3) Arbors for external grinding

(4) Oxidized machine centers to prevent galling of a running surface of a spinning part being ground.

Troubles originating from resonant vibrations can usually be corrected by improved jigs or by backing up thin, slender sections to prevent deflection.

Adjustments in wheel speed, work speed and feed, truing conditions, and grinding fluid will usually compensate for the selection of a wheel with less than optimum grinding characteristics.

Wheel Speeds. For a given grinding wheel and coolant, an optimum grinding speed can produce much higher grinding ratios (G ratios) than a speed a few hundred feet per minute (fpm) higher or lower. For the aluminum oxide wheel, 32A46J8VBE, the optimum speeds appear to be between 3000 and 6000 fpm for grinding oil coolants.

Wheel speeds of 4000 fpm can be used with aluminum oxide wheels and heavily sulfurized oils to produce a good combination of surface finish and dimensional tolerance with relatively low residual stresses. Low residual stresses are produced at low wheel speeds (2000 fpm) using aluminum oxide grinding wheels and a highly sulfurized oil (Ref. 54).

Feeds. Two types of feeds are involved in grinding: the downfeed and the crossfeed. The former is similar to the depth of cut in machining while the latter corresponds to the feed.

The lightest downfeeds [0.0005 inch per pass (ipp)] seem to give the highest grinding ratios over a wide range of crossfeeds (between 0.025 and 0.25 ipp). However, as the downfeed is successively increased from 0.0005 ipp the grinding ratio falls and does so more rapidly as the unit crossfeed is increased. Hence, a crossfeed of around 0.050 ipp normally is used together with downfeeds between 0.0005 and 0.001 ipp. Heavier downfeeds can cause burning and excessive wheel wear (Refs. 16,54).

Grinding Fluids. It is important to use a grinding fluid that will cool efficiently and inhibit the chemical reaction between the alloys and the abrasive wheel. Alloy steels should never be ground dry. Dry grinding results in excessive residual stresses and smeared surfaces.

Water alone is not suitable, and ordinary soluble oils do not produce good grinding ratios. Chemical coolants, diluted 40:1, likewise produce rather low grinding ratios (Ref. 16). The basic composition of these coolants is described on page 24.

The highly sulfurized oils diluted 1:1 with light machine oil give some of the highest grinding ratios. Some of the highly chlorinated grinding oils also have proved quite satisfactory.

The degree of concentration or dilution of a grinding fluid plays an important part in the grinding action. Maximum G ratios are usually obtained with undiluted oils. When grinding oils are diluted with plain mineral oil, some of their advantages are lost but not as much as when grinding titanium (Ref. 16).

The rust inhibitors can be used at about 3 percent concentration, but very low grinding ratios usually result (Ref. 16).

All fluids should be filtered to remove grit, and to prvent "fishtail" marks* on finished surfaces. Fluids should be changed more often than is customary in grinding steel.

Additional Requirements. Grinding operations should be supervised and controlled very carefully. When the grinding procedure used is questionable, quick checks to detect possible surface cracking can be made by dye and fluorescent penetrants.

Wheels used to grind the annealed alloys must be dressed more frequently than those used to grind steels because of wheel loading.

If an extremely accurate ground finish is required, it is advisable, particularly if the material is of hard temper, to remove the workpiece from the grinder after the final roughing cut and set it aside to cool to room temperature. This procedure allows redistribution of internal stresses in complete freedom. The resulting distortion, if it occurs, can be corrected in the final grinding operation.

The low stress (LS) grinding procedure is sometimes recommended for the hardened alloy steels (Ref. 16). This method consists of a very light downfeed procedure in successive steps as follows:

(1) 0.001 inch per pass to the last 0.002 inch to be removed

(2) 0.0005 inch per pass

(3) 0.0005 inch per pass

*They actually look more like pollywog marks.

(4) 0.0004 inch per pass

(5) 0.0003 inch per pass

(6) 0.0002 inch per pass

(7) 0.0001 inch per pass.

Data on speeds and feeds found suitable for aluminum oxide wheels are shown in Table XXIV.

BELT GRINDING

Introduction. Stainless steel alloys can be belt ground to close dimensional tolerances.

The carrier-type machine is usually used in the abrasive belt grinding of sheet. The work is held on a table that oscillates back and forth under the grinding belt. A billy roll directly under the contact roll maintains the pressure between the work and the belt.

These belt grinders have produced flat surfaces on sheet with only 0.004-inch maximum deviation over areas up to 36 x 36 inches.

Another important application involves the finishing of aerofoil sections of compressor and turbine blades. Two methods are used for their manufacture. The grinding-to-form technique employs an abrasive belt that is guided by a contact wheel. The latter is controlled by a stylus and tracer mechanism. The second technique causes the abrasive belt to pass over a contour block.

Machine rigidity is important in all cases for achieving close-dimensional tolerances (Refs. 81,82).

Abrasive-Belt Contact-Wheel Systems. Paper-backed belts, used dry or with a grinding oil, are suitable for flat-sheet work. Cloth-backed belts are used when a more rugged backing is needed. Cloth belts are generally available in two types: drills (X weight), which are the heavier and stiffer of the two, and jeans (J weight). The flexible J-weight backing is used for contour polishing; the X weight provides the best belt life and fastest cutting (Refs. 83,84). Fully waterproof, cloth-backed belts are necessary when water-base grinding fluids are used. All belts are usually manufactured to close-thickness tolerances to permit grinding to precise dimensions.

TABLE XXIV SURFACE-GRINDING CONDITIONS FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS (REFS. 16 54 63)

Alloy Group	Alloy Group Representative	Alloy Condition[a]	Typical Grinding Wheel Marking[b]	Downfeed, ipp Rough	Downfeed, ipp Finish	Crossfeed, ipp	Table Speed, fpm	Wheel Speed, fpm	Grinding Fluid[c]
			Nonstainless Alloy Steels						
	Cr-Mo low-alloy steels								
A1	A-4130	Ann; HT	A46JV	0.001	0.0005	--	60	6000	IIa
	Cr-Ni-Mo low-alloy steels								
C1	A-4340	Ann; HT	A46JV	0.001	0.0005	--	60	6000	IIa
F1		(350 Bhn)							
G1		HT ($52R_C$)	32A46H8VBE	0.001	0.0005	0.040	40-50	6000	IIa
			32A46J8VBE	0.002	0.001	0.040	40-50	4000	IIa
	5Cr-Mo-V die steels								
D2	H-11	Ann (160-220 Bhn)	A46JV	0.001	0.0005	--	40	5000	IIa
			A46IV	0.001	0.0005	--	40	5000	IIa
G2		HT ($52R_C$)							
	Cr-Ni-Mo steel								
E1	D6a	HT ($52R_C$)	32A46I8VBE	0.001	--	0.050	40	6000	IIa, IIIb
			32A46H8VBE	0.001	--	0.050	40	4000	IIa, IIIb
			Stainless Steel Alloys						
	Straight-chromium grades								
B4	405	Ann; (150-220 Bhn)	A46JV	0.001	0.0005	--	50	5000	IIc
B5, D5	410, 440B	Ann (150-220 Bhn)	A46IV	0.001	0.0005	--	50	5000	IIc
			A46HV	0.001	0.0005	--	40	6000	IIc
		HT (45 R_C)	32A46H8VBE	0.001	--	0.050	60	6000	IIc
			32A46H8VBE	--	0.001	0.050	60	3000	IIc
	Precipitation-hardenable grades								
D6	17-7 PH	Ann	A46HV	0.001	0.0005	--	40	6000	IIc
F6		HT (440 Bhn)	A46HV	0.001	0.0005	--	40	6000	IIc
		HT (444 Bhn)	32A46H8VBE	0.002	--	0.025	20	6000	IIc
		HT (444 Bhn)	32A46H8VBE	--	0.001	0.025	20	3000	IIc
	Chromium-nickel grades								
D7	347	Ann	A46JV	0.001	0.0005	--	50	5000	IIc
			Austenitic Stainless Steel Superalloys						
	Nonheat-treatable grades; age-hardenable grades								
D8	19-9DL	ST	A46IV	0.001	0.0005	--	50	4000	IIc
E9	A-286	STA	32A46H8VBE	0.001	--	--	20	6000	IIc
E9	A-286	STA (321 Bhn)	32A46H8VBE	--	0.0005	--	20	3000	IIc.

(a) Ann = annealed; HT = heat treated, ST = solution treated; STA = solution treated and aged.
(b) See Table XXII on markings for grinding wheels.
(c) See page 25 for the specific fluids coded.

Contact Wheels. The contact wheel, which supports the belt at the pressure point, regulates the cutting rate and controls the grain breakdown (Refs. 83,84).

Plain-faced contact wheels are normally used when unit pressures are high enough to promote the necessary breakdown of abrasive material for best grinding action. They usually produce a better surface finish than do most serrated wheels. They minimize extreme shelling.* They also permit off-hand grinding and polishing of curved and contoured parts.

The contact wheel should be small in diameter and as hard as practicable. This combination provides almost a line contact and, hence, a high unit pressure between the abrasive grits and the work.

Suitable contact-wheel materials for abrasive belts include rubber, plastic, or metal. Rubber is usually recommended because metal contact wheels show little significant increase in stock removal and grinding rate at the price of considerable noise, vibration, poorer surfaces, and higher power consumption.

Rubber contact wheels are available in various degrees of hardness, measured in terms of Durometer units. These values may range from 10 (sponge rubber) to about 100 (rock hard). The softest rubber (other than sponge) has a value of 20. The harder the contact wheel, the faster an abrasive belt will cut and the coarser the surface finish will become. Softer wheels produce better surface finishes. However, even soft wheels become effectively harder as spindle speeds increase and they present more support to the belt. Softer rubber wheels can be used for blending and for spotting operations to remove isolated defects. The best rubber contact wheel is one that is firm enough to give restricted contact and good penetration by the grit, but resilient enough to eliminate shelling failure of the belt at the high loads (Refs. 83,84).

Abrasive Belts. Aluminum oxide abrasive belts are usually recommended under normal feeds and for the belts speeds considered optimum for stainless steel alloys. These belts must possess a dense texture (closed coat).

Roughing and spotting operations are normally carried out on belts coated with medium- or fine-grain abrasives. The fine-grit size, 80, is slightly superior to the medium-grit size, 40. Extra

*Shelling is the tendency for the abrasive grains on the abrasive belt to loosen and flake off.

fine-grain abrasives (grits 120 to 280) are used for finish belt-grinding operations.

Synthetic-resin bonds provide maximum durability for abrasive belts used on stainless steel alloys. They are available in a waterproof or nonwaterproof backing.

Setup Conditions.

Belt Speeds. Cutting speed affects the rate of metal removal, belt life, and surface finish. Lower belt speeds reduce cutting temperatures as well as the tendency toward burning or marring the surface by incandescent chips.

Although the optimum speed varies with the contact wheel, grit size, and work thickness, a speed of 4000 to 6500 fpm generally gives good results.

Feeds. Feeds in belt grinding are controlled indirectly by adjusting the pressure. The correct feed permits an economical rate of metal removal and avoids loading the belt with chips. Feeds should be controlled to give the best dimensional tolerances. If feed pressures must be increased, it may be advisable to use a softer contact wheel.

A definite correlation exists between grinding pressure and belt speed. Higher speeds require less pressure and vice versa. Feed pressures between 80 and 120 psi have been used, depending on the belt speed.

Grinding Fluids. Lubrication is a most significant factor in abrasive belt grinding. Dry grinding, except for certain intermittent operations (blending, spotting, etc.), is not recommended for (Ref. 81).

A grinding fluid should be used when taking continuous cuts over fairly large areas. It reduces grinding temperatures and quenches sparking. Sulfochlorinated grinding oils possessing high flash points (above 325 F) can be used and should be applied close to the grinding point for rapid spark quenching.

Soluble-oil emulsions in water are normally poor grinding fluids but can be used where the alternative is to grind dry.

With waterproof belts, water-base fluids containing certain inorganic compounds may give good results. Aqueous-solution lubricants seem to give the best performance in grinding setups where high loads are used, for example, stock-removal operations. The following water-base fluids have been used:

(1) Sal soda (1 lb of sal soda to 25 gallons of water)

(2) Sodium phosphate (up to 12 percent solution)

(3) Potassium phosphate (yp to 30 percent solution).

All sodium and potassium phosphate solutions are caustic enough to remove paint from machine tools. The more concentrated solutions, however, are not much worse in this respect than weaker (5 percent) solutions and are considerably more effective as grinding lubricants.

Grinding fluids can be applied by spraying or by immersing the belt.

Operating Data. Sometimes a roughing operation is first conducted with a 50-grit belt to remove gross surface imperfections. An intermediate grind (80 grit) is then used to reduce the grind marks, followed by a finishing operation using a 120-grit belt.

The correct treatment of belt troubles requires an understanding of the difference between glazing and loading. Glazing occurs on abrasive belts when the grinding pressure is insufficient to break down the abrasive particles properly. A loaded belt contains workpiece material on and in between the abrasive grains, a condition that impairs cutting ability. Proper lubrication is one way to minimize loading (Ref. 84).

The same inspection procedures recommended in the precision-grinding section also apply to belt grinding.

Table XXV summarizes the pertinent conditions for the belt grinding of hardened alloy steel and stainless steel alloys.

TABLE XXV. BELT-GRINDING CONDITIONS FOR HARDENED ALLOY STEELS AND STAINLESS STEEL ALLOYS (REFS. 82, 85)

Alloy				Abrasive Belt				Contact Wheel			
Group	Group Representative	Alloy Condition[a]	Type Operation	Abrasive Type	Abrasive Size[b]	Coat or Texture[c]	Belt Backing[c]	Type[c]	Hardness[c], Durometer	Belt Speed, fpm	Grinding Fluid
						Nonstainless Alloy Steels					
C1 & D2	4340 & H-11	HT (400 Bhn)	--	Al_2O_3	50	Closed	X, J	--	--	6500	Light chlorinated grinding oil
						Stainless Steel Alloys					
B4 B5 D5 D6 D7	All stainless steels	Ann or HT	Roughing	Al_2O_3	50 to 80	Closed	X, J	Cog-tooth or serrated rubber	70-90	4000-5000	Light grinding oil
			Polishing	Al_2O_3	80 to 120	Closed	X, J	Plain or serrated rubber	30-60	4000-5000	Ditto
			Fine polishing	SiC	150 to 280	Closed	X, J	Smooth rubber	20-40	4500-5500	Heavy grease or oil mist

(a) Ann = annealed; HT = heat treated.
(b) Fine grits tend to fail by shelling at pressures that coarser grits will easily withstand.
(c) See page 108.

ABRASIVE SAWING

Introduction. Nonstainless alloy steels and stainless steel alloys can be cut with abrasive wheels. However, the peripheral cutting edge and adjacent surfaces of the wheel can load with metal during the cutoff operation in much the same manner described on page 100 (see precision-grinding section). The occurrence of wheel loading may cause high residual stresses on the cut surfaces. Stress-relief treatments may be necessary to prevent delayed cracking of cut surfaces. When proper techniques are used, however, the cut surfaces are bright, smooth, and straight. Surface finishes between 10 and 14 microinches can be obtained. To avoid heat tinting or burning, wet cutting using rubber-bonded wheels is suggested (Ref. 80).

Machine-Tool Requirements. Rigid setups and abrasive cutoff machines having wheel heads capable of oscillating and plunging motions are usually recommended. It is also advisable that the cutoff machine be equipped with hydraulic feed mechanisms that can be set to produce any desired cutting rate.

Cutoff Wheels. The choice of the right combination of abrasive grit, wheel hardness, and type of bond will do much to alleviate difficulties. These characteristics are identified for cutoff wheels in much the same way as shown in Table XXII for grinding wheels.

Aluminum oxide cutoff wheels are generally used on both nonstainless and stainless steels. Resinoid-bonded wheels are recommended for dry cutting since these wheels absorb much of the heat generated in cutting. Rubber-bonded wheels should be used for wet cutting. Table XXVI contains wheel data for the alloy steels and stainless steel alloys.

Conditions of Setup. The choice of speeds and feeds depend on the diameter of the work and the method of cutting (wheel oscillation and work rotation). Some combinations that have given satisfactory results are given below.

Speed. Speeds from 5000 to 5500 fpm have been used successfully in abrasive cutoff operations for the austenitic superalloys. Wheel speeds of 10,000 fpm for 12-inch wheels and 16,000 fpm for 10-inch wheels can be used on conventional stainless steels (Ref. 80).

TABLE XXVI. CUTOFF WHEELS FOR NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS (REF. 63)

Alloy			Dry Cutting (Resinoid Wheels)[a]			Wet Cutting (Rubber-Bonded Wheels)[a]			
Group	Group Representative	Brinell Hardness	Abrasive Type	Grit Size	Wheel Grade	Abrasive Type	Grit Size	Wheel Grade	Coolant[b]
			Nonstainless Alloy Steels						
	Low-alloy steels								
A1	A-4130	<250	A	46	N	A	60	Q	I
C1	A-4340	250-400	A	36	R	A	46	S	I
		>400	A	30	R	A	46	S	I
	5Cr-Mo-V die steels								
D2	H-11	<250	A	46	N	A	60	Q	I
		250-400	A	46	R	A	46	R	I
		>400	A	60	P	A	54	P	I
			Stainless Steel Alloys						
	Straight-chromium grades								
B4	405	<250	A	36	P	A	46	P	I
B5, D5	410, 440	<250	A	36	P	A	46	P	I
		250-400	A	30	R	A	46	Q	I
		>400	A	30	R	A	46	Q	I
	Precipitation-Hardenable grades								
D6	17-7 PH	<250	A	36	P	A	46	P	I
		250-400	A	30	R	A	46	Q	I
		>400	A	30	R	A	46	Q	I
	Chromium-nickel grades								
D7	347	<250	A	36	P	A	46	P	I
			Austenitic Stainless Steel Superalloys						
	Nonhardenable grades; Age-hardenable grades								
D8	19-9 DL	260-340	--	--	--	A	54	N	I
E9	A-286								

(a) See Table XXII for complete abrasive-wheel data.
(b) See page 25 for coolant information.

Feeds. Successive overlapping shallow cuts should be taken in order to keep the work-wheel contact area as small as possible at all times. Maximum feeds permitted by the machine's capability are used depending on setup conditions and wheel speed.

Cutting Rate. Cutting rates are available for stainless steels. These rates are approximately 0.25 square inch per second for dry cutting and 0.125 square inch per second for wet cutting (Ref. 80). These data can be used as guides for the other steels covered in this report.

Cutting Fluids. A rust-inhibitor type of coolant should be supplied at the rate of about 20 gallons per minute to the work-wheel contact area in order to reduce cutting temperatures enough to avoid heat cracking of the cut surfaces and to offset warpage, loss of corrosion resistance in stainless steels, and other undesirable thermal effects (Ref. 15).

The coolant should penetrate the wheel-work contact area. It should be applied equally to both sides of the wheel to avoid cracked cuts and wheel breakage.

Soluble-oil coolants can be used, but they have a tendency to foam. Soluble-oil coolants are available that minimize the objectionable rubber-wheel odor.

The size of the workpiece influences the choice of cutting techniques. A small stock around 1 inch in diameter can be cut dry without an oscillating head or rotation of work. Bars from 1 to 3 inches in diameter should be cut wet and may require either an oscillating or a nonoscillating wheel. Both should be tried in order to determine which is better for the given situation.

Bars larger than 3 inches in diameter usually require rotation of the work as well as an oscillating wheel. The work should be rotated slowly, or indexed, so that the wheel can cut toward the center without cutting too far beyond center.

BAND SAWING

Introduction. Band sawing can be used for making both straight and contour cuts in nonstainless alloy steels and stainless steels. Generally, band sawing of these materials is recommended only when shearing or abrasive wheel cutting cannot be used efficiently. Sawing is usually considered a rough trimming operation requiring finish trimming, either by hand or by machine, to meet the requirements of aircraft-quality parts.

Austenitic-type steels are very difficult to saw because of their high ductilities. Difficulties in sawing these materials can be minimized by selecting a saw band with the proper pitch, and by using a feeding pressure suited to the work thickness involved. The combination of band velocity and feed also influences the economic tool life.

Machine-Tool Requirements. Rigid high-quality band-saw equipment with motors providing at least 2 horsepower should be used. The machines should provide automatic positive feeding and band-tensioning features. In addition, they should have a positive-flow, recirculating-type coolant system.

Saw Bands. Precision and claw-tooth saw bands are recommended. The widest and thickest band that can produce the smallest radius desired on the part should be selected. The following band widths will cut the minimum radii indicated:

Saw Widths, inch	Minimum Radii Cut, inch
1/16	Square
3/32	1/16
1/8	1/8
3/16	5/16
1/4	5/8
3/8	1-7/16
1/2	2-1/2
5/8	3-3/4
3/4	5-7/16
1.0	7-1/4

Wider saw bands provide greater stability when the saw is pretensioned.

Figure 19 illustrates some of the common terms used in describing sawing operations.

Saw-Band Design. The two important design features of a saw band are the pitch or the number of teeth per inch and the set of the teeth. The selection of the pitch for a saw-band cutting high-temperature metals depends mainly on the cut thickness opposed

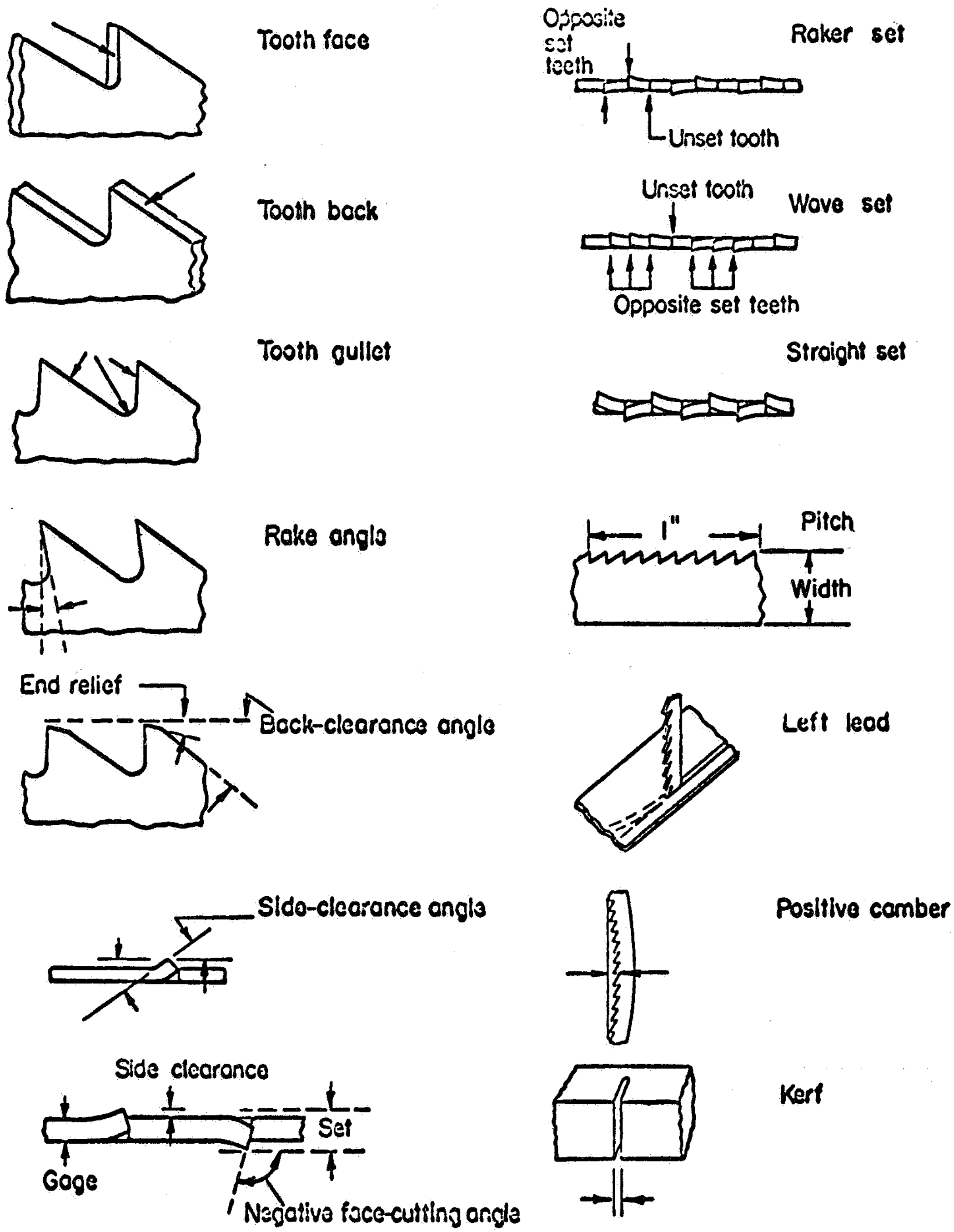


FIGURE 19. COMMON ILLUSTRATIONS USED IN SAWING

by the saw teeth. This thickness varies in the case of round bars. If the pitch is too coarse, the feeding force on each tooth will be excessive. On the other hand, if the pitch is too fine, the chips will crowd or fill the gullets. In general, the coarsest pitch consistent with desired finish should be selected; however, at least two teeth should always contact the cut, and the chip load at any one time should not exceed 0.005 ipt.

The saw set makes a clearance so the trailing surfaces of the band do not bind in the cut. It determines the kerf and hence the amount of metal removed. A fine-pitch saw band with a light set usually gives the best finish, particularly, when used with higher band velocities and low feed rates. This combination also produces a slot (or kerf) that approaches the overall saw-set dimension.

The following tabulation gives some data for raker and wave set, precision-type band saws used.

Width,	Gage,	Pitches - Raker Set (Nominal)							Pitches - Wave Set (Nominal)				
inch	inch	6	8	10	12	14	18	24	8	10	12	14	32
1/16	0.025	--	--	--	--	--	--	0.038	--	--	--	--	0.038
3/32	0.025	--	--	--	--	--	0.042	--	--	--	--	--	0.042
1/8	0.025	--	--	--	--	0.043	0.042	0.042	--	--	--	--	--
3/16	0.025	--	--	0.044	--	0.043	0.042	0.042	--	--	--	--	0.042
1/4	0.025	--	--	0.044	0.043	0.043	0.042	0.042	--	--	--	--	0.042
3/8	0.025	--	0.045	0.044	--	0.043	0.042	0.042	--	--	--	--	--
1/2	0.025	0.045	--	0.044	--	0.043	0.042	0.042	--	0.044	--	0.043	--
5/8	0.032	--	0.055	0.055	--	0.054	0.052	0.050	--	0.057	--	0.057	--
3/4	0.032	0.055	0.055	0.055	0.054	0.054	0.052	--	0.057	0.057	0.057	0.057	--
1	0.035	0.058	0.055	0.058	--	0.057	--	--	--	0.063	--	--	--

A right-left raker set combined with the coarsest pitch relevant to the work thickness and the desired finish is usually adequate for most applications other than thin sheet and thin-wall tubing. Saws with wave set teeth are best for sawing thin sections.

Tool Materials. Saw bands with high-speed steel teeth and flexible backs are recommended for sawing the austenitic-type stainless steels. An appropriate heat treatment produces a microstructure that remains strong at elevated temperatures and a reasonably flexible band. High-carbon saw bands can be used for the martensitic-type steels and stainless steels.

<u>Setup Conditions</u>. Hand- or gravity-type feeds do not produce satisfactory results when sawing these alloys. Vibration-free

machines with positive mechanical feeds are necessary to prevent premature band failure.

Maximum rigidity is favored by using the widest and thickest band permitted by the band wheel and the radii to be cut. The band should be pretensioned to approximately 12,000 psi to minimize unnecessary bending of the saw band in the cut. Guide inserts should be adjusted to a snug fit to insure accurate cuts and minimum "lead" (Figure 19). For the same reasons, the band support arms should be close to the work.

Cutting Speeds. Band velocity is a critical variable in sawing high-temperature alloys. Excessive cutting speeds cause high cutting temperatures and unwanted vibrations.

Band velocities used for sawing the alloys considered in this report* usually range from 50 to 320 fpm depending on the alloy, work thickness, surface finish, cutting rate, saw pitch, band material, and desired tool life.

Feeds. The saw should constantly "bite" into the work; otherwise, the blade will rub and work harden the material being cut.

Unit feeds in the range of 0.00014 to 0.0005 inch per tooth can be used successfully. The smaller feeds give the best tool life, but the heavier feeds increase productivity and may be more economical. Excessive feeds clog the teeth with chips before they emerge from the kerf and reduce cutting rates.

Feeding forces must be reduced as the saw pitch decreases to prevent overloading individual teeth. On the other hand, feeding pressures so light that the teeth do not penetrate the work cause work hardening, excessive abrasion, and rapid dulling.

Cutting Rate. The cutting rate in band sawing is determined mainly by the thickness of the workpiece. Higher cutting rates (up to 2.7 square inches per minute) are achieved in sawing solid bars 1 inch or greater in thickness (or diameter) since more teeth can be loaded uniformly at the same time. For thinner sections, the limited number of engaged teeth requires a reduction in cutting rate to reduce the feed per tooth. In this case cutting rates should not exceed the 0.9 square inch per minute minimum rate for all alloys. Higher

*See pages 170, 180, 181.

rates may cause inaccurate cutting and damage the saw set. In general, minimum cutting rates must be reduced when band sawing tubing and structural mill shapes than for bars and plates.

Cutting Fluids. Cutting fluids used in band sawing these alloys include soluble oils or sulfurized oils (Refs. 63,86). Fluids discharging forcefully from shroudlike nozzles will penetrate the kerf and prevent chips from adhering to the tooth faces and gullets. An atomized spray of soluble oil under 40 psi of air pressure also has been used with good results. A pressure-resistant oil may be brushed on the saw teeth to prevent chip welding.

Additional Requirements. Heavy oxide films may cause problems in band sawing. This trouble can be solved by breaking or removing this surface at the line of cut with a used saw blade or by other suitable means.

During the sawing operations, the saw band must not skew in the cut. If the cutting time starts to increase rapidly, the saw band should be replaced.

A problem may be encountered in sawing thin sheet material (around 0.010 inch). Scrap template stock, or a narrow-kerf accessory block used under the material to be sawed, can alleviate this condition.

Conditions suitable for band sawing sheet, plate, bars, and tubing are suggested in Tables XXVII to XXX inclusive.

TABLE XXVII. RECOMMENDED[a] SPEEDS, FEEDS, AND CUTTING RATES FOR BAND SAWING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS

Group	Representative Alloy	Band Speed[b], fpm	Cutting Rate, in.^{2}/min	Unit Feed, ipt
A1	A-4130 steel	320	0.9-2.7	0.00014
C1	A-4340 steel	270	0.9 to	to
D2	5Cr-Mo-V die steel	240	2.7	0.0005
B4	Type 405 stainless steel	175		
B5	Type 410 stainless steel	175		
D5	Type 440 stainless steel	110		
D6	17-7 PH stainless steel	110		
D7	Type 347 stainless steel	150		
E9	A-286 stainless steel superalloy	75		

(a) Based on 1/4 to 1/2-inch thickness.
(b) For high-speed steel bands.

TABLE XXVIII. PITCHES OF BAND SAWS RECOMMENDED FOR SAWING DIFFERENT WORK THICKNESSES

Work Thickness, inch	Appropriate Pitch, teeth per inch
7/64 to 5/32	18-32
5/32 to 3/16	14-18
1/4 to 3/8	10-14
1/2 to 1.0	6-14
1.0 and greater	6-10

TABLE XXIX. RECOMMENDED MODIFICATIONS OF CUTTING RATES FOR PIPE, TUBING, AND STRUCTURAL SHAPES

Minimum Wall Thickness to be Sawed, inch	Fraction of Minimum Cutting Rates Shown in Table XXX
Up to 3/16	0.40
1/4 to 3/8	0.50
1/2 to 5/8	0.60
3/4 to 1.0	0.70
1.0 and greater	1.00

TABLE XXX. BAND SAWING NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS (REF. 63, 86)

Alloy		Type of Steel Band(a)	Band Speed, fpm for pitch indicated in parenthesis — Work Thickness, inches				Cutting Rate, $in.^2$/min and unit feed, ipt for thickness shown — Less than 1 inch		1 to 3 Inches		Cutting Fluids(b)
Group	Group Representative (Annealed)		0 to 1/4	1/4 to 1/2	1/2 to 1	1 to 3	Cutting Rate	Unit Feed	Cutting Rate	Unit Feed	
			Nonstainless Alloy Steels								
	Cr-Mo low-alloy steels										
A1	A-4130	High C	150(18)	125(14)	100(10)	75(6)	0.9	0.00014	2.7	0.00025	IIa
		HSS	--	320(10)	270(8)	220(6)		to		to	I, IIa
								0.00022		0.0005	
	Cr-Ni-Mo low-alloy steels										
C1	A-4340	High C	140(18)	120(14)	90(10)	60(6)	0.9	0.00014	2.7	0.00025	IIa
		HSS	--	270(10)	230(8)	180(8)		to		to	I, IIa
								0.00022		0.0005	
	5Cr-Mo-V die steels										
D2	H-11	High C	125(18)	100(14)	75(10)	60(6)	0.9	0.00014	2.7	0.00025	IIa
		HSS	--	240(10)	200(8)	160(6)		to		to	I, IIa
								0.00022		0.0005	
			Stainless Steel Alloys								
	Straight-chromium grades										
B4	405	High C	130(18)	90(14)	50(10)	--	0.9	0.00014	2.7	0.00025	IIa
B5	410	HSS	--	175(10)	135(8)	110(6)		to		to	
								0.00022		0.0005	
D5	440B	High C	150(18)	--	--	--	0.9	0.00014	2.7	0.00025	IIa
		HSS	--	110(10)	100(8)	90(6)		to		to	
								0.00022		0.0005	
	Precipitation-hardenable grades										
D6	17-7 PH	High C	145(18)	--	--	--	0.9	0.00014	2.7	0.00025	IIa
		HSS	--	110(10)	90(8)	70(6)		to		to	
								0.00022		0.0005	

(a) High C — high-carbon steel saw band
HSS — high-speed steel saw band.
(b) See page 25 for specific types.

UNCONVENTIONAL OR NONMECHANICAL MACHINING

The need for shaping or fabricating parts from hardened high-strength and heat-resistant metals and alloys has created new and difficult metal-removal problems. The development of new, harder and stronger alloys have made the traditional or conventional machining methods less efficient. These methods utilize the shearing action of a sharp tool against the workpiece to achieve chip-by-chip metal removal. To cope with these hard and tough materials, new or improved metal-working methods have been devised.

Among the novel nonmechanical methods or processes developed for machining into accurate and complex shapes the tough steels and alloys frequently used in aircraft, missiles, and rockets, etc., are electrochemical machining (ECM), chemical milling, electric-discharge machining (EDM), ultrasonic machining, electron-beam machining. The next sections of this report will deal with the first three of the above methods, respectively, with special emphasis being placed on the machining or shaping stainless and alloy steels.

ELECTROCHEMICAL MACHINING (ECM)

ECM PROCESS

Introduction and General Comments. Metal removal in ECM is by electrochemical reaction or dissolution brought about by the passage of an electrical current through a suitable electrolyte between the workpiece (anode) and a shaped tool or tools (cathode). ECM can be likened to an electroplating process operating in reverse. For a general discussion of ECM, see References 87 to 90, inclusive.

Rate of metal removal in ECM is proportional to the applied current and is in accordance with Faraday's laws. The high velocities (e.g., 40 to 200 ft/sec) of electrolyte flow used in ECM, together with the close spacings (e.g., 0.001 to 0.040 inch) between the workpiece and the other electrode(s), make possible the passage of high currents at relatively low voltages (e.g., 3 to 30 volts), thus resulting in high metal-removal rates. For example, current densities of 50 to 1500 amp/sq in. or more are common for ECM; whereas current densities of about 0.1 to 2.0 amp/sq in. are representative of many electroplating operations. Electrolyte pumping pressures for ECM range from about 10 to 450 psi.

The schematic representations shown in Figures 20 and 21 will illustrate the workings of the ECM process. At the start of the drilling operation (see Figure 20), the tool is brought to the desired gap distance (e.g., 0.002 to 0.015 inch) from the steel workpiece surface. Then, the voltage is applied causing current to flow. As the drilling operation proceeds, the workpiece dissolves and the tool is steadily advanced to maintain a constant machining gap. Electrolyte is pumped down the drilling tube and leaves through the space between the tool and the hole wall as shown in Figure 20. Insulation on the outside of the tool is employed to minimize side cutting and to produce a hole with straight sides.

Figure 21 shows the electroshaping of a turbine blade. The rough blade forging is positioned between the two shaped tools in a specially designed plastic fixture. Electrolyte is pumped through the spaces between the blade and the tools. As the ECM operation proceeds and metal is removed from the blade, the two cathode tools are moved in simultaneously to maintain relatively constant machining gaps. This process continues until the blade has the desired configuration as set by the cathode tool shapes and the operating parameters used.

The same general procedures as described above can be used for die-cavity sinking, trepanning, broaching, and other shaping or contouring operations. For contouring and die-cavity work, the flow-past type (i.e., flow is roughly parallel to the electrode surfaces) of electrolyte flow, as shown in Figure 21, is often used rather than the flow-through type illustrated in Figure 20.

Three-dimensional cavities can be produced by ECM using a single-axis movement of the tool electrode, which closely resembles the reverse image of the desired cavity shape. ECM is especially suited for drilling of multiple holes or irregular-shaped holes. Representative parts produced by various ECM operations in stainless and alloy steels are shown later in this report.

Equipment. A typical general-purpose ECM installation that can be used for cavity-sinking, trepanning, broaching, drilling, contouring, etc., is shown in Figure 22 (Ref. 91). The ECM work zone is inside the transparent-plastic enclosure at the center. Adjacent to it is the control console. The electrolyte pumping and handling system are at the left, while the power pack is at the right.

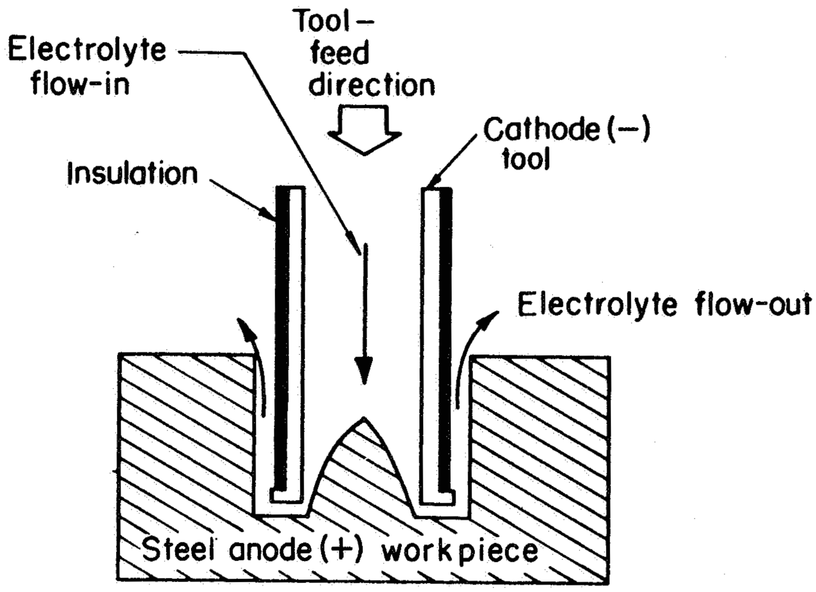


FIGURE 20. ECM DRILLING OPERATION

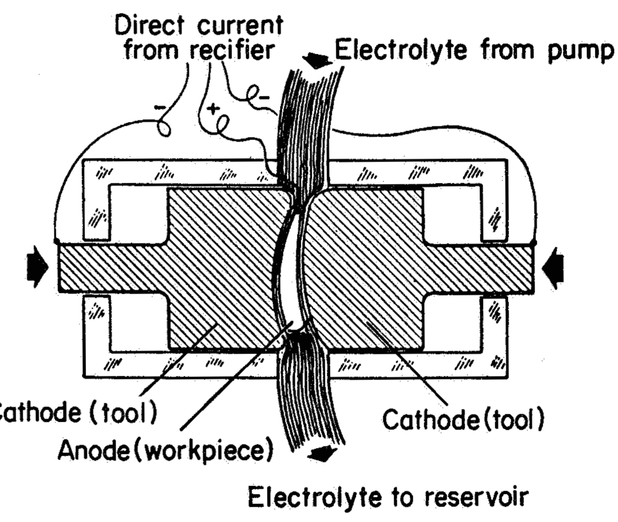


FIGURE 21. ELECTROSHAPING OF A TURBINE BLADE

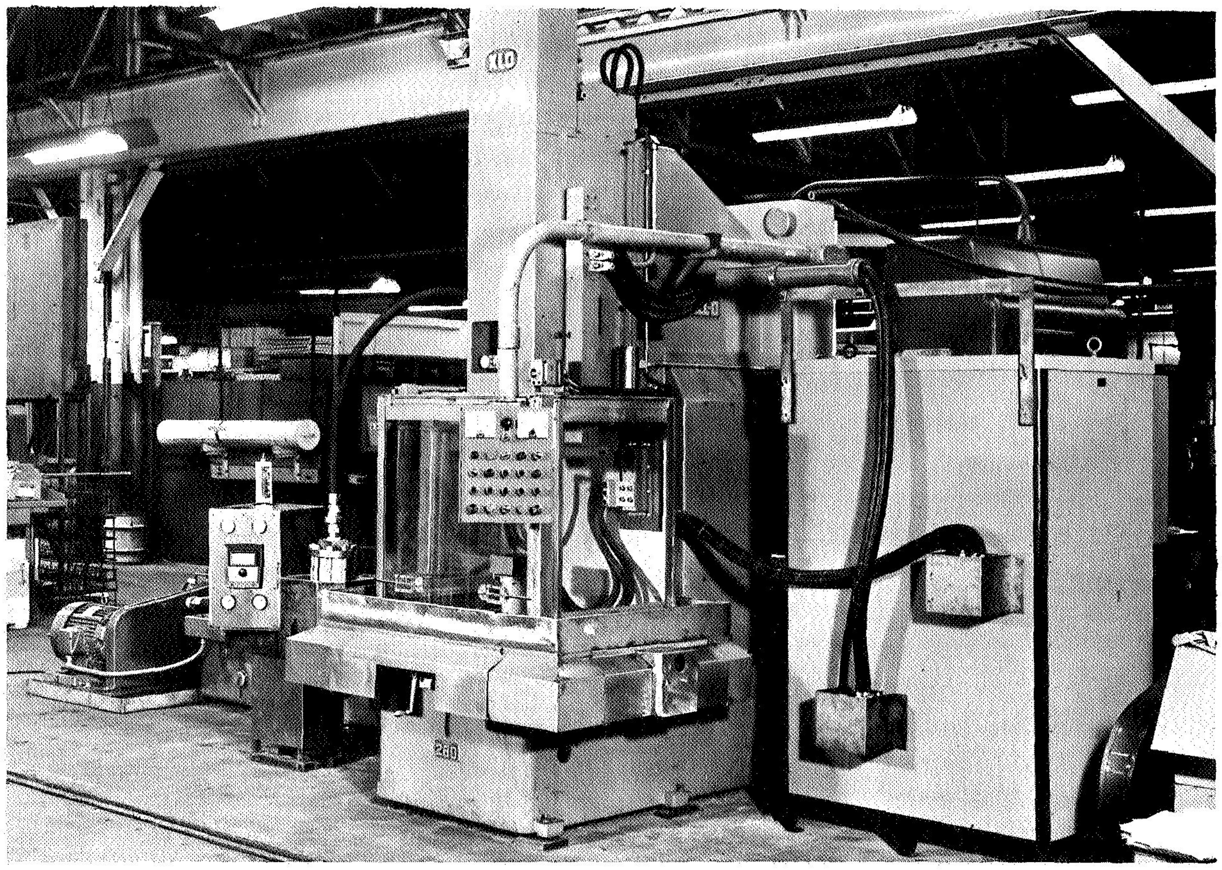


FIGURE 22. GENERAL PURPOSE ELECTROCHEMICAL MACHINING INSTALLATION (REF. 91)

Courtesy of the Ex-Cell-O Corporation, Lima, Ohio.

ECM units with current capacities ranging from 100 to 10,000 amperes are readily available commercially. Units with 10,000-ampere capacities are in operation in industry, and larger units of 20,000 amperes or more are being planned and should be in operation soon.

Tooling and Fixturing. ECM electrode tools generally conform closely to the reverse image of the shape to be produced. Detailed information on the design of cathode tools is proprietary and has not been generally disclosed. The results of some work on a computerized approach to tool design has been reported by Bayer, et al. (Ref. 92). Cathode tools are generally made of copper, stainless steel, brass, copper-tungsten alloys, or other conductive and corrosion-resistant materials.

Custom or specially designed fixturing is generally employed to obtain good control of the electrolyte flow between the electrodes needed for accurate and efficient ECM operation. Tooling costs for some types of ECM operations may be expensive. For that reason, ECM is generally better suited to production work than to single or small-lot jobs, unless the unique capabilities of ECM justify the cost of using the method for machining small lots of parts of difficult-to-machine metals or shapes. The fact that the cathode tool does not wear or change during ECM is important for production work. It means that once a suitable tool is developed it can be used (or reused) almost indefinitely to make replicate parts without any need to compensate for tool wear.

Electrolytes. Electrolyte composition, operating conditions, and the chemistry and microstructure of the steel alloy being processed determine ECM performance and also the surface finishes produced. Specific information on ECM of the stainless and alloy steels is mostly proprietary, and has not been generally disclosed. Neutral- and acid-type electrolytes have been used successfully.

Some electrolyte formulations are based on sodium chloride or sodium nitrate, mineral acids, plus other compounds added to enhance the electrolyte's ability to give good cutting performance and also good surface finishes. Neutral-salt or alkaline electrolytes involve precipitate- or sludge-handling problems, whereas with acid electrolytes the problem of plating out on the cathode tool may occur. Some specific data on electrolytes' compositions are given later. Proprietary formulations are marketed for ECM of specific stainless and alloy steels, as well as other metals and alloys.

Metal-Removal Rates and Tolerances. Penetration rates for stainless steels, iron, nickel, and other metals and alloys are shown in Figure 23. These rates are theoretical for the metals in the indicated valence states; they are based on anode dissolution current efficiencies of 100 percent. In general, ECM dissolution efficiencies are high and range from about 85 to 100 percent. The penetration rate shown for iron (Fe^{+2}) corresponds very closely to values for high-strength steels.

Typical metal-removal rates for cavity-sinking or blade-contouring operations range from about 0.005 to 0.100 inch or more per minute. Drilling rates are usually higher and range from about 0.030 to 0.500 inch or more per minute. Planing or broaching operations can be performed at lineal speeds of 1 to 6 inches per

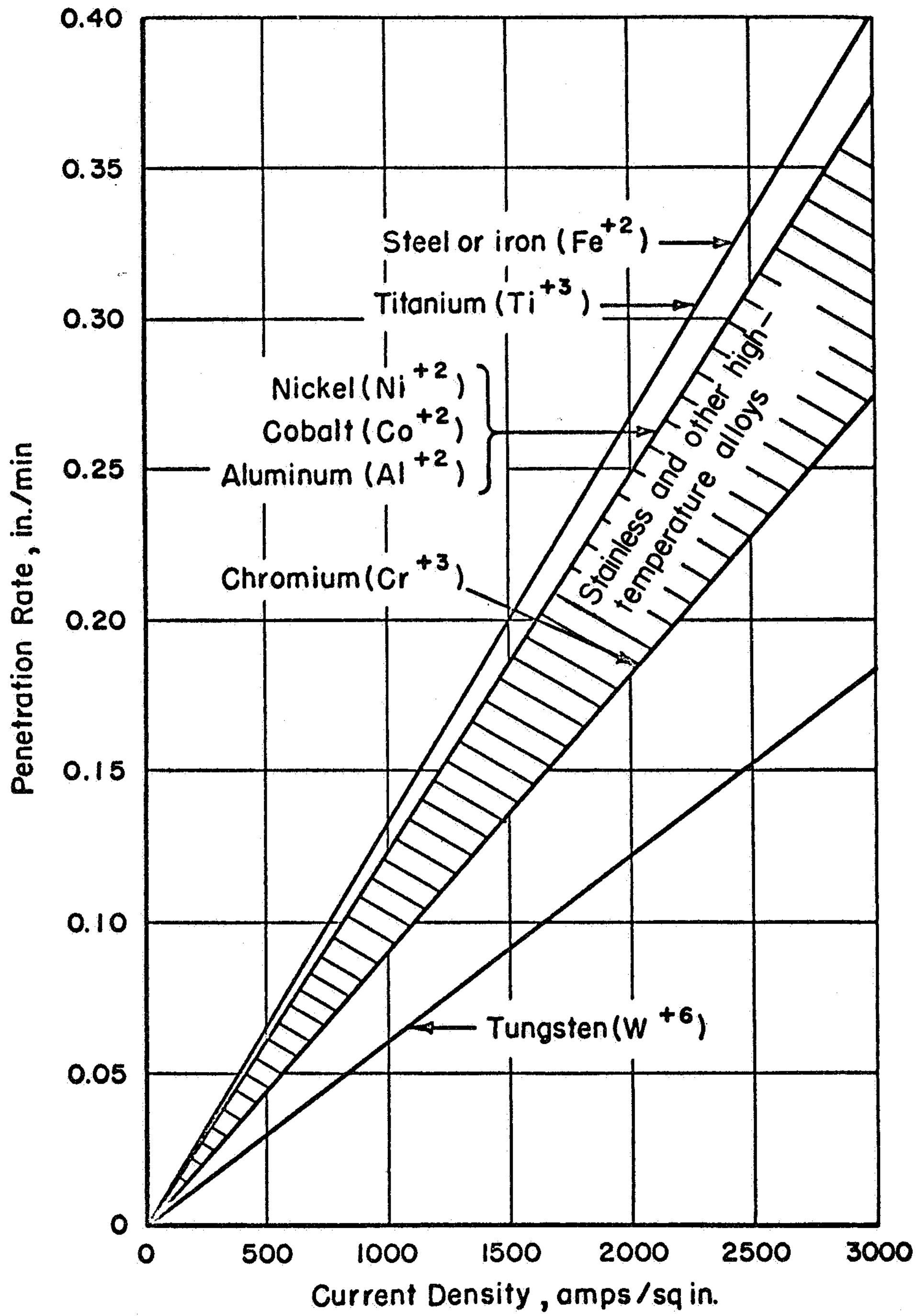


FIGURE 23. PENETRATION RATES FOR VARIOUS METALS AND ALLOYS

minute with removal of about 0.010 to 0.060 inch of metal from the surface.

Tolerances in ECM depend greatly on the type operation being carried out. Hole diameters can be held to ±0.001 inch. Tolerances for other shapes can range from about ±0.002 inch to about ±0.030 inch depending on part configuration and also on the particular type of ECM operation involved.

Characteristics of ECM. Some unique characteristics or advantages of ECM for machining or shaping the stainless and alloy steels are:

(1) Burr-free machining

(2) Stress-free machining

(3) No thermal damage to workpieces

(4) No tool wear

(5) No intrinsic effect of material hardness on ECM rates and performance.

Since the cathode tool does not touch the workpiece, no mechanical stresses are imparted and no distortion occurs in fragile or thin parts. The fact that the tool does not wear, erode, or change during ECM means that once a suitably shaped tool is developed, it can be used or reused indefinitely to produce replicate parts without any need to compensate for tool wear.

ECM OPERATING CONDITIONS FOR STAINLESS AND ALLOY STEELS

As indicated earlier, much of the specific data and information on electrolyte compositions and operating conditions for ECM are proprietary and have not been disclosed publicly. Some information on ECM of specific metals and alloys is available from the ECM equipment makers. However, some of the data and information that are available on electrolytes and operating conditions for the stainless and alloy steels are presented and discussed below.

Representative operating data for work by Bayer, et al. (Ref. 93) on producing exemplary stainless and iron-base alloy parts by two different ECM techniques are given in Table XXX. Production of exemplary parts was done to demonstrate the overall capabilities (e.g., feed rates, tolerances, surface finishes, etc.) of the ECM process.

Good surface smoothnesses were obtained in both the embossing operation on the Carpenter No. 20 material (i.e., 12 to 20 microinches AA*) and also on the cavity-sinking run on A-286 (i.e., 10 to 36 microinches AA). A sodium chloride electrolyte (0.67 lb/gal NaCl) was used for the Carpenter No. 20 material; whereas a sodium nitrate solution (5.0 lb/gal $NaNO_3$) was used for the A-286 work.

Clifford, et al. (Ref. 94) investigated various electrolytes for cutting (slicing operation with either single or multiple disks) of A-286 alloy and 4340 steel. The following electrolyte composition gave good cutting results with A-286 and 4340 steel:

Sodium chloride: 200 to 227 g/l NaCl

Boric acid: 25 g/l H_3BO_3.

Typical operating conditions were as follows:

Cathode wheel speed: 7200 surface ft/min

Voltage: 10 to 12 volts

Temperature: 70 ± 10 F

Feed rate: 0.071 in./min

Length of cut: 0.0 to 1.2 inch.

Similar cutting performances were obtained in slicing the 4340 bar stock in the hardened (52.5 R_C) or annealed (55 R_A) conditions. For comparable operating conditions, poorer cutting performance (maximum feed rate of 0.027 in./min) was obtained on A-286 using acid-type electrolytes containing either sulfuric acid and tartaric acid, or hydrochloric acid and tartaric acid.

Figure 24 shows a forging die for a digger tooth of a clam-shell bucket produced in a Hard-Tem die steel (hardened) block by ECM (Ref. 95). The original block was about 8 x 8-1/2 x 8 inches. The

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*AA – arithmetical average.

TABLE XXXI. REPRESENTATIVE OPERATING DATA AND SURFACE ROUGHNESSES PRODUCED BY ECM ON STAINLESS AND IRON-BASE-ALLOY PARTS (REF. 93)

Material	ECM Operation	Electrolyte					Applied Voltage or Voltage Range[a], volts	Current Range[a] amp	Feed Rate, in./min	Depth of Cut, in.	Surface-Roughness Range, microinches (AA)[b]	Comments
		Component	Concentration, lb/gal	Tank Temperature, F	Inlet-Pressure Range[a], psi	Flow Rate,[a] gal/min						
Carpenter No. 20	Embossing grooves in flat plate	NaCl	0.67	84	155/130	1.5/1.5	6.0 for 1 min, 18.0 for balance	83/123	None	0.07	12-20	Cutting time 10 min; surface-roughness data for embossed grooves
A-286 (iron-base alloy)	Sinking a 2-dimensional cavity into a flat surface to a depth of 0.5 inch	$NaNO_3$	5.0	100	240/240	3.9	12.0	741	0.040	0.510	10-36	Good finish on cavity surface; value of current is for end of run

(a) Data given in the table are representative of one or more runs of a particular ECM operation on the alloys. During the ECM runs, some operating-condition values change considerably; the values shown are generally those noted at the start and end of the run.
(b) Surface-roughness height was rated in microinches arithmetical average (AA) deviation from the mean line.

cavity was sunk at a penetration rate of about 0.010 in./min. The maximum depth of penetration into the block was 2-1/2 inches. The surface finish was good, being about 30 microinches rms.

Multihole drilling of a 304 stainless steel burner plate (1/8 inch thick) is illustrated in Figure 25 (Ref. 96). The 198 holes were drilled in a single pass using a salt-type electrolyte; the 0.050-inch hole diameters were held to ±0.015-inch tolerance. The burr-free character of the holes produced by ECM was an important consideration on this job. The 2-minute ECM drilling time contrasts with 90 minutes of conventional drilling time, plus an additional 50 minutes needed for deburring the underside.

ELECTROLYTIC GRINDING (EG)

The term "electrolytic grinding" (EG), as used in this report, refers to metal removal by a combination of electrochemical action and mechanical abrasion. Electrolytic grinding might be considered as a specialized form of electrochemical machining. In EG a conductive wheel (cathode) impregnated with abrasive particles is rotated against the workpiece (anode). The physical setup resembles that of a conventional grinder, except for the electrical connections to the wheel and workpiece. The abrasive particles maintain the proper working gap between the cathodic base and the workpiece. In addition, by abrading or scraping off the film or solid-type electrolysis products from the workpiece, they expose fresh workpiece surfaces to further electrochemical oxidation. Generally, about 85 to 95 percent of the metal removal is by electrochemical action, with abrasion accounting for the remainder. Because of this, the wheel pressures in EG are generally much lighter and also electrolytic wheels generally last five to ten times, or more, longer than conventional wheels.

Electrolytes for electrolytic grinding are usually aqueous solutions of salts such as sodium nitrite, sodium nitrate, sodium silicate, etc., plus addition agents. Electrolyte formulations aim at providing good conductivity, good grinding performance, and also at being nontoxic to personnel and noncorrosive to machines and their surroundings. Special proprietary formulations are marketed for electrolytic grinding of stainless and alloy steels, and also for many other metals and alloys.

Data and results from a study of electrolytic grinding of hardened 4340 steel and A-286 alloy are given in Table XXXII (Ref. 97). See

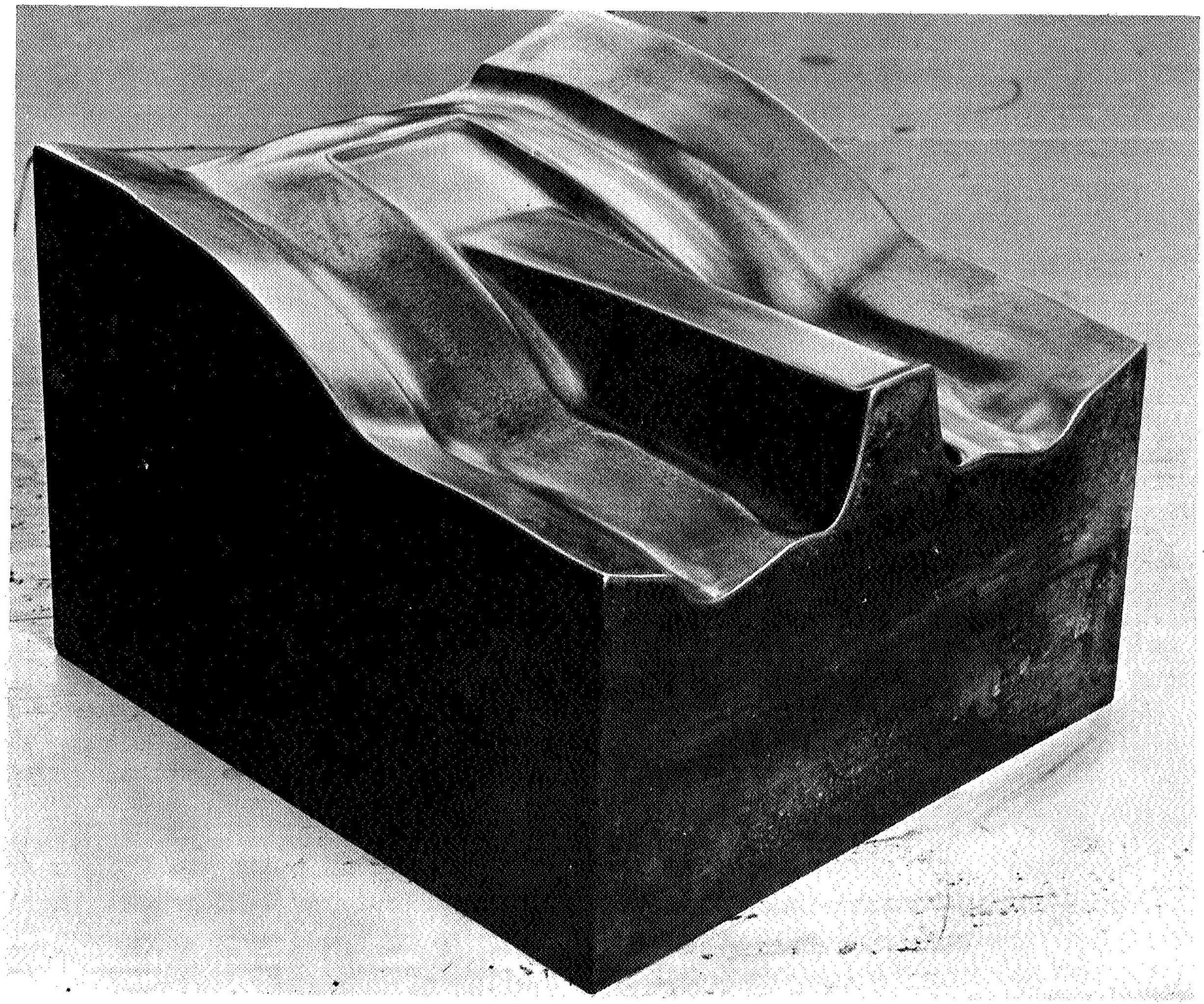

FIGURE 24. ECM SINKING OF FORGING DIE FROM SOLID BLOCK (REF. 95)

Courtesy of the Steel Improvement and Forge Company, Cleveland, Ohio.

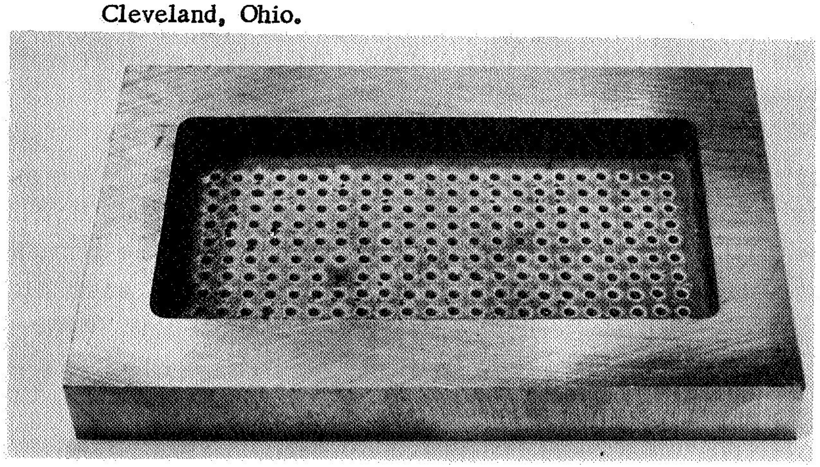

FIGURE 25. ECM DRILLING OF 304 STAINLESS STEEL BURNER PLATE (REF. 96)

Courtesy of the Ex-Cell-O Corporation, Detroit, Michigan.

Footnote (a) for detailed data on the heat-treatment condition of these alloys. Metallographic examination showed that the electrolytically ground surfaces were satisfactory. The surfaces were uniform in appearance and free of pits and intergranular attack.

TABLE XXXII. ELECTROLYTIC GRINDING OF 4340 STEEL AND A-286 ALLOY (REF. 97)[a, b]

Material	Feed Rate, in./min	Depth of Cut, in.	Voltage, volts	Current, amp	Return Pass[c]	Surface Produced
4340	4.5	0.005	9	150	No	Satisfactory
A-286						
Top	3.7	0.005	5	80	No	Satisfactory
Bottom	3.7	0.005	5	150	Yes	Satisfactory

(a) The 4340 steel was procured in the mill-annealed condition and heat treated to 260,000 to 280,000 psi prior to grinding. The A-286 (AMS-5525) was procured in the solution-treated condition and aged prior to grinding.

(b) Grooves were machined in the plates using an electrolytic grinder equipped with an A3HC-60-1/2 metal-bonded aluminum oxide wheel. Full-strength solution of Anocut No. 90 (Anocut Engineering Co., Chicago, Illinois), electrolytic salts were used.

(c) A return pass means feed in one direction and rapid traverse (14 in./min) return to the starting point with current and electrolyte flowing.

Rivkin (Ref. 98) reported that use of an aqueous solution containing 15 weight percent potassium nitrate (KNO_3) plus 0.5 weight percent sodium nitrite ($NaNO_2$), added as a corrosion inhibitor, gave good results for electrolytic grinding of R-18 (Russian) high-speed steel. Good surface finishes were obtained at about 14 volts with a bronze-bonded aluminum oxide wheel under the following operating conditions:

Wheel speed: 147 ft/sec

Infeed: 0.0002 in./table stroke

Table speed: about 10 ft/min.

Higher table speeds lead to burns and cracks.

The favorable electrolytic-grinding results, presented above, indicate that the process would be ideally suited for grinding stainless and alloy steel parts where there might be danger of heat checks or surface cracks produced by conventional mechanical grinding. Other favorable features of electrolytic grinding are its ability to produce burr-free surfaces and to grind thin or fragile parts, such as honeycombs (because only light wheel pressures are involved).

ELECTROCHEMICAL HONING

The more recently introduced electrochemical-honing (ECH) process combines electrochemical metal removal with the controlled-surface-generating capabilities of abrasive honing. As with electrolytic grinding, most of the metal is removed by electrochemical action. The electrolytes used in ECH are of the less corrosive types, similar to those used for electrolytic grinding (e.g., sodium nitrate, sodium nitrite, etc.), rather than the more corrosive ones used in ECM. This is possible because the oxides formed by anodic dissolution are scrubbed away by the abrasive honing stones.

A close-up view of an ECH tool and the working-zone area used for honing a hardened transmission gear is shown in Figure 26 (Ref. 99). The manner in which rotation is imparted to the workpiece from two small driven gears can be seen in Figure 26. The workpiece rotation is needed so that the bore generated will be concentric with the pitch cylinder of the gear teeth.

The cathode tool (upper center of Figure 26) is fitted with three expanding "shoes" that serve as the electrodes. The shoes are mounted on gaging arms that include small orifices for pneumatic gaging during honing. Electrolyte is introduced to the workpiece-abrasive-stone zone through a series of small holes in the tool body between the stones. A series of spacers on the face of each shoe establishes the gap (0.003 to 0.005 inch) between the shoe and work surface to provide the proper electrolyte flow. The spacers ride on the workpiece surface under light pressure. Figure 27 shows the cathode tool in its operating position and the ECH process in action. Hydraulic power provides for cathode-tool reciprocation and workpiece rotation (Ref. 99).

The inside bore (1-5/8-inch ID x 2-inch length) of a hardened transmission gear (SAE 5135 steel, hardness 60 R_C) processed by ECH is shown in Figure 28 (Ref. 99). Straightness and roundness

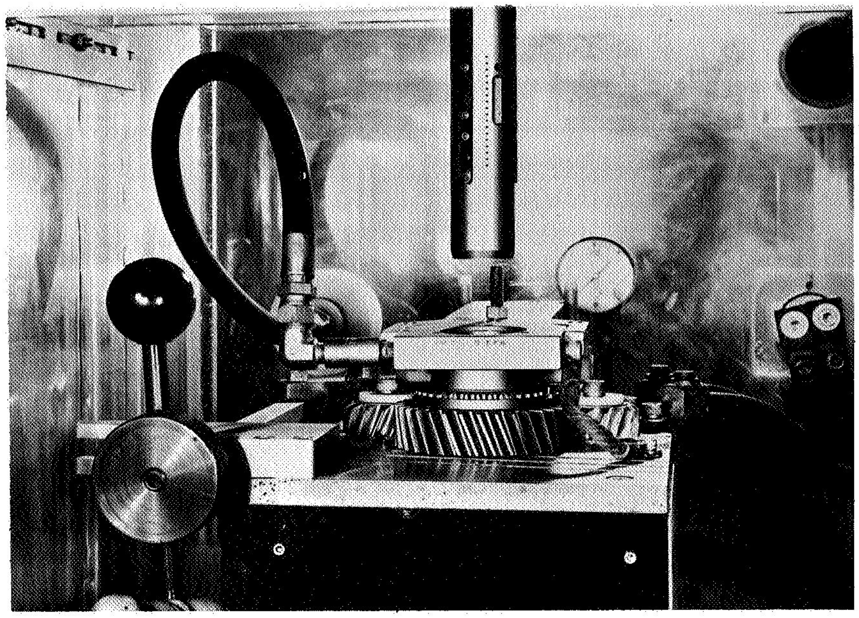

FIGURE 26. CLOSE-UP VIEW OF ECH TOOL AND WORKPIECE ARRANGEMENT (REF. 99)

Courtesy of the Micromatic Hone Corporation, Subsidiary of Ex-Cell-O Corporation, Detroit, Michigan.

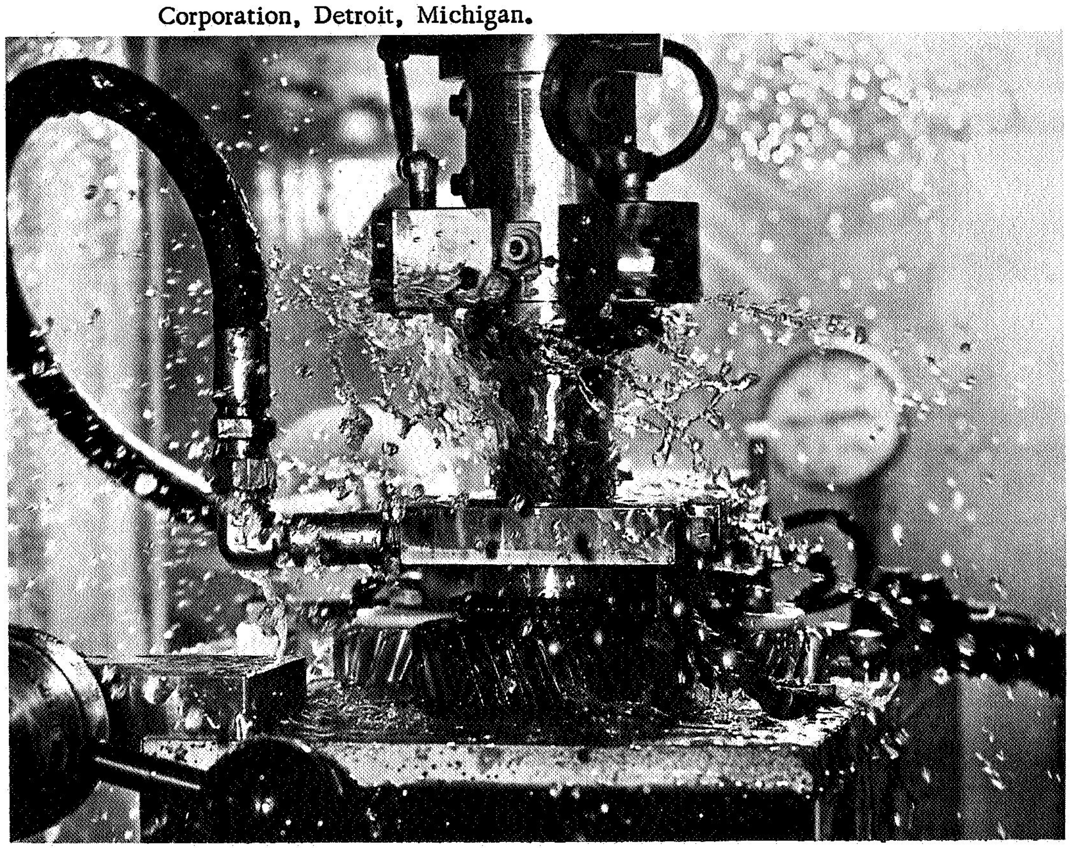

FIGURE 27. ELECTROCHEMICAL HONING IN ACTION (REF. 99)

Courtesy of the Micromatic Hone Corporation, Subsidiary of Ex-Cell-O Corporation, Detroit, Michigan.

were held to within 0.003 inch. The surface smoothness was 10 to 12 microinches. ECH removed 0.008 inch of stock from the diameter in about 20 seconds; the time for doing the same job by conventional honing was estimated at 160 seconds. About 1200 amperes at 11 volts were used in processing the transmission gears. The current densities ranged from about 150 to 200 amp/sq in. The electrolyte pumping pressure was about 150 psi.

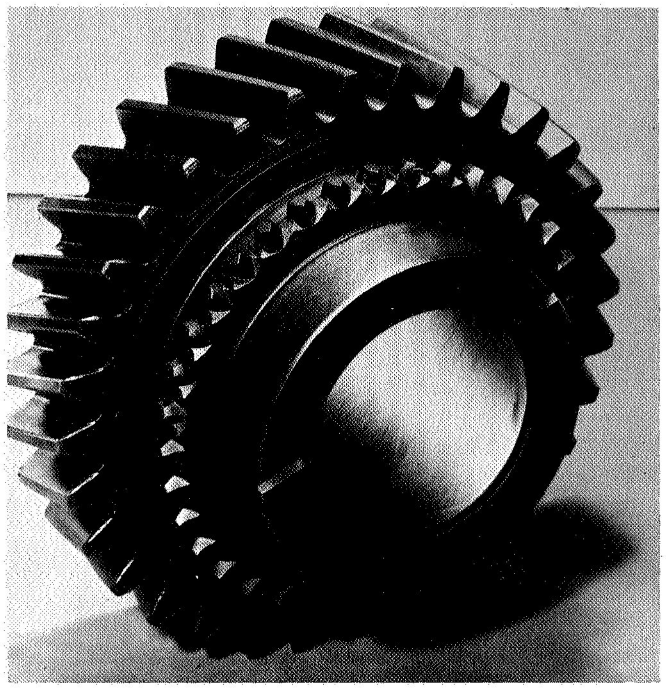

FIGURE 28. ELECTROCHEMICALLY HONED TRANSMISSION GEAR (REF. 99)

Courtesy of the Micromatic Hone Corporation, Subsidiary of the Ex-Cell-O Corporation, Detroit, Michigan.

If the conventionally honed surface appearance with a cross-hatch pattern is desired, as shown in Figure 28, it can be obtained readily by turning off the electrical current for the last few seconds of operation.

Some advantages of electrochemical honing over conventional honing are:

(1) Substantial increase in abrasive efficiency and faster metal-removal rate for hard materials

(2) Workpieces stay relatively cool and the surfaces produced are essentially free of stresses, because metal is removed with a minimum of mechanical action.

(3) Burr-free surfaces.

COMMENTS ON MECHANICAL PROPERTIES OF ECM-PROCESSED PARTS

Published data on the mechanical properties of ECM-processed stainless and alloy steels are scarce. DMIC Report 213 (Ref. 100) indicated that ECM generally had no significant effect on mechanical properties such as yield strength, ultimate tensile strength, sustained-load strength, hardness, ductility, etc., for most metals and alloys including the stainless and alloy steels.

Since metal removal in ECM is by anodic dissolution, the stainless or high-strength steel workpieces are not subjected to hydrogen discharge that occurs at the cathode tool. Thus, in a properly conducted ECM operation, there is no danger of loss of ductility or delayed fracture of the high-strength steel alloy parts from hydrogen embrittlement.

DMIC Report 213 (Ref. 100) indicated further that metals and alloys (including the stainless and alloy steels) for which mechanical surface treatments or cold working increase fatigue strength will appear to be weakened about 10 to 20 percent by ECM or electropolishing. The mechanical finishing methods often impart compressive stresses to the metal surface; this raises fatigue strength. In contrast, ECM or electropolishing, by removing stressed layers or forming none, leaves a stress-free surface that allows measuring the true fatigue strength of the metal. The conclusion is that ECM and electropolishing are safe methods to use for processing metals. Where maximum fatigue strength is important, use of a post-ECM or post-electropolishing treatment, such as vapor honing or shot peening, is indicated. These subsequent mechanical treatments can restore or impart compressive stresses to the surface, so that ECM or electropolished parts, thus treated, will exhibit comparable or better fatigue properties than mechanically finished parts.

SUMMARY

Electrochemical machining in its various forms is well suited for machining the hard and tough stainless and alloy steels. This is particularly so for operations such as: production of complex shapes or cavities, blade shaping, broaching, drilling, or trepanning of round- or irregular-shaped holes, deburring, etc.

In general, good surface finishes are obtained by ECM on the stainless and alloy steels. Surface roughnesses for the stainless steels generally range from about 10 to 30 microinches rms; the high carbon steels run about 20 to 50 microinches rms.

It is expected that electrochemical machining in all its forms, which are already being widely used in industry, will be more extensively used for machining steel and other tough alloy parts in the years to come. This is because the ECM processes are readily adaptable for production work and automation, and do not require highly skilled personnel for routine production operations.

CHEMICAL MILLING

INTRODUCTION

Chemical milling refers to the shaping, machining, fabricating, or blanking of metal parts to specific design configurations by controlled chemical dissolution with suitable chemical reagents or etchants. The process is somewhat similar to the etching procedures used for decades by photoengravers, except that the rates and depths of metal removal are generally much greater for chemical milling.

Much of the early chemical-milling work was done on aluminum and magnesium parts for the aircraft industry. Chemical milling saved on labor, materials, and time. It also provided engineers with an increased design capability and flexibility in fabricating parts for advanced aircraft, missiles, and space vehicles. During the last 5 or 6 years, use of chemical milling has increased for the production of parts of high-strength, heat-resistant metals and alloys, including the stainless and alloy steels.

Chemical milling is especially suited for removing metal from the surface of formed or complex shaped parts (e.g., forgings, castings, extrusions), from thin sections, and from large areas or shallow depths. For example, chemical milling has been used widely to produce pocketed areas and integral land areas on formed and flat aircraft parts. The weight savings are especially important in aircraft and space-vehicle design. Metal can be removed from an entire part, or else selective metal removal can be achieved by etching the desired areas while the other areas are masked against chemical attack. Tapering, step etching, and sizing of sheets or plates can be performed readily.

Simultaneous etching of a part from both sides can be carried out with a twofold reduction in the milling time, while also minimizing the danger of warpage due to release of residual stresses (if present) in the part. The amount of metal removed, or milling depth, is determined by the time of immersion in the etching solution. Generally, no elaborate tools or complex holding fixtures are required. Many parts can be processed simultaneously; the production rate being giverned by the available tank dimensions or volumes.

Some of the technical information on chemical-milling procedures, etchant-solution compositions, and techniques are of a proprietary nature.*,**,***

PROCESSING PROCEDURES

The overall chemical milling process consists of four main operations or steps, namely:

(1) Cleaning (or surface preparation)

(2) Masking

(3) Chemical etching

(4) Rinsing and stripping or removal of the mask.

Masking and etching are probably the most critical operations for successful chemical-milling work.

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*Chem-Mill, a registered trademark of North American Aviation, Inc., which has granted Turco Products, Inc., Wilmington, California, the exclusive right to sublicense other firms to use the Chem-Mill process.

**Chem Size, a proprietary chemical-dissolution process developed by Anadite, Inc., South Gate, California, for improving the tolerances of as-rolled sheet and plate, and of parts after forming.

***Chem Tol, a proprietary chemical-dissolution process developed by the United States Chemical Milling Corporation, Manhattan Beach, California, for production of sheet material and parts to close tolerances.

CLEANING

Cleaning of stainless and alloy steel surfaces is usually done by conventional methods such as vapor degreasing, wiping with a solvent-dipped cloth, dipping in an alkaline solution or an emulsion-type cleaning solution to remove all grease and dirt. Where scale, passive films, oxidation products, or other foreign materials are firmly attached, acid pickling or mechanical cleaning (e.g., vapor blasting) might be needed to produce clean surfaces. Where scale is heavy, a caustic descaling bath might be used to loosen, modify, or remove the scale; pickling then follows to produce a clean surface. Thorough rinsing followed by drying completes the cleaning operation. Failure to properly clean the stainless and alloy steel surfaces will cause masking problems and uneven attack by the etchant solution.

MASKING

Masking for the stainless and alloy steels involves the application of an acid-resistant coating to protect the areas where no metal removal is desired. Masks are generally applied by either dip, spray, or flow-coating techniques. Brush or roller-type applications are also used. The particular coating method to be used depends considerably on part size and configuration.

Plastic coatings (Ref. 101), such as chlorinated rubber resins, polyvinyl chloride, and polyethylene are used as maskants, because of their ability to hold up well in the strong acid and oxidizing solutions used for milling the stainless and alloy steels. Flow-coating with neoprene elastomer has also been used successfully as a maskant for stainless steels (Ref. 102). Multiple coats (three or more) are usually employed to provide sufficient mask thickness and good coverage. The intermediate coats are usually air dried. After the final coat, the mask is usually cured by baking at about 200 to 300 F for about 1 to 3 hours to improve mask adhesion, tensile strength, and chemical resistance.

Other desirable characteristics of a good maskant in addition to good adhesion and good chemical and heat resistance are: (1) suitability for accurate pattern transfer on contours and complex configurations; it must maintain straight lines in the etched design, regardless of its complexity, (2) good scribing qualities, (3) easy removal after scribing to present clean surfaces for etching, and also good stripping after etching to yield clean surfaces for possible subsequent processing, (4) good stability in the liquid form, and (5) economical in cost.

The patterns on the masked workpiece are usually applied by means of templates, followed by scribing, and then manual peeling of the mask from the areas to be etched. Mask patterns can also be applied to metallic workpieces by silk-screen techniques and by use of photosensitive resists. These latter techniques are usually employed on jobs where fine detail and shallow cuts are required. Photographic techniques are frequently employed for the blanking or piercing of relatively thin parts (e.g., thickness usually less than about 1/16 inch). Photoresist masks are often used in the production of printed circuits, name plates, dials, etc., by chemical etching.

ETCHING

A good chemical-milling solution should be capable of removing metal at a predetermined and uniform rate, without adversely affecting dimensional tolerances and the mechanical properties of the part. Good chemical stability and ability to operate well over a wide concentration and temperature range are other desirable features of an etchant system. Pitting, intergranular attack (IGA), uneven etching of the part surface, or production of rough surfaces are all bad characteristics of an etchant system.

The etchants generally used for chemical milling of stainless and alloy steels are aqueous solutions of mineral acids such as:

(1) Modified aqua regia (hydrochloric acid-nitric acid mixtures)

(2) Triphase acid mixtures (hydrochloric acid-nitric acid-phosphoric acid)

(3) Triphase acid mixtures (nitric acid-sulfuric acid-phosphoric acid).

The exact solution compositions are proprietary. In addition to these main constituents, the solutions may contain special additives to enhance their etching characteristics and inhibit hydrogen pickup. The presence of dissolved metal (e.g., iron, chromium, nickel, etc.) in the etchant solutions helps their performance; consequently "partially aged" baths (i.e., mixing new reagents with a portion of a spent or aged bath) are generally employed.

Solutions containing ferric chloride ($FeCl_3$) as the primary reactant, and mixtures of ferric chloride and nitric acid are also used for milling stainless and low-alloy steels. These ferric-chloride-containing solutions are frequently employed in the spray etching of fine detailed parts and in blanking-type operations.

Etchant solutions are usually circulated over the part surface to promote uniform dissolution. Parts are also periodically moved, turned, or rotated to promote uniform metal removal over the entire surface. In some applications, the etchant is sprayed or splashed against the part. Careful etchant-composition and temperature control are needed to maintain uniform and predictable rates of metal removal.

The typical production tolerance for chemical milling is ±0.002 inch. However, prior to chemical milling, the actual raw-stock tolerance must be added to the production tolerance. The following figures can be used as a guide to depth-of-cut limitations for chemical milling (Ref. 103):

Sheet and plate	0.500 inch maximum depth/surface
Extrusion	0.150 inch maximum depth/surface
Forging	0.250 inch maximum depth/surface.

Because chemical etching proceeds sideways at about the same rate it proceeds down, the minimum widths that can be machined are about three times the etch depths. Eshelman (Ref. 104) in commenting on the chemical milling of alloys of aluminum, magnesium, titanium, and the superalloys indicated that tolerances on parts up to 10 x 20 feet in size have run as close as +0.000 -0.002 inch. Achieving such tolerances calls for very careful control of bath composition and operating variables.

Etching rates for stainless and alloy steels range from about 0.2 to 3.0 mils/min. Typical industrial rates are about 0.4 to 1.5 mils/min. A generalized comparison of the performance characteristics of etching systems for milling stainless and alloy steels, titanium alloys, and aluminum alloys is shown in Table XXXIII. As indicated, the solution compositions used for milling the stainless and alloy steels are generally more complex than those used for the aluminum or titanium alloys. The ferritic steels and heat-treated steels generally have rougher surfaces and require more critical etchant and temperature control than the alloy or annealed steels.

TABLE XXXIII. DATA AND CHARACTERISTICS OF VARIOUS SYSTEMS FOR CHEMICAL MILLING OF STEEL, TITANIUM, AND ALUMINUM ALLOYS[(a)]

Item	Alloy Sheets	Titanium Alloys	Aluminum Alloys
Principal reactants	Nitric acid - hydrochloric acid or nitric acid - hydrochloric acid - phosphoric acid	Hydrofluoric acid - nitric acid	Sodium hydroxide or hydrochloric acid
Etch rate, mils/min	0.5-1.3	0.6-1.2	0.8-1.2
Optimum etch depth, in.	0.125	0.125	0.125
Ethant temperature, F	150 ± 10	115 ± 5	195 ± 5 (NaOH) 110 ± 10 (HCl)
Average surface roughness, rms microinches	50-150	40-100	80-120

(a) Data are from Sanz and Shepherd (Ref. 105) and also from data gathered or compiled by the authors from other sources.

Additional data and information on etching of specific steel alloys are given and discussed in later sections of this report dealing with effects of chemical milling on mechanical properties of metals and alloys and also on hydrogen pickup.

RINSING AND STRIPPING

After etching is completed, the parts are thoroughly rinsed in water. The mask is then either stripped by hand or immersed in a suitable solvent to facilitate its removal. Proprietary solvents are marketed for handling the various types of maskants used.

EFFECTS ON MECHANICAL PROPERTIES

The consensus is that chemical milling (provided good uniform metal dissolution is achieved, i.e., no intergranular attack, selective etching, or pitting) does not adversely affect the mechanical properties of metals and alloys. Published data on effects of chemical milling on mechanical properties are rather scarce and more of the same data are needed.

In work carried out by Grumman Aircraft Engineering Corporation (Ref. 106), photomicrographs of chemically milled stainless and carbon steel surfaces and cross sections showed no adverse effects caused by chemical milling. The materials studied included: 15-7 PH, 17-7 PH, 321 austenitic stainless steel, AISI 4130, AISI 4340, AISI 6434, Vascojet 1000, and 19-9 DL stainless steel. Microhardness data showed no changes between the chemically milled and nonmilled materials.

The results of production chemical milling at North American Aviation of a variety of steel alloys, such as 300-series stainless steel, 4130 and 4340, 17-7 PH, 17-4 PH, 431, etc., have been reported by Sanz and Shepherd (Ref. 105). No intergranular attack was observed in photomicrographs of the production-milled alloys. Tests on AISI 4130 showed that chemical milling had no significant effect on the tensile properties. Compression and shear data on 17-7 PH (TH 1075 condition) showed that chemical milling had no significant effect on these properties.

Results of a study (Ref. 107) carried out at Convair as part of the CENTAUR program indicated that chemical milling presented no serious problems in regard to its effects on mechanical properties of Type 301 EH and 310 EH steels, and that the process was applicable to CENTAUR lightweight tank design. The room-temperature tensile properties of Type 301 EH stainless were reduced less than 5 percent by chemical milling, whereas no appreciable change was noted for Type 310 EH steel. Results of static tensile and fatigue tests at room and liquid-hydrogen temperatures indicated that the step between the 0.016-inch-thick as-rolled and the 0.010-inch-thick chemically milled areas presented no serious problems for either the 301 EH or 310 EH material.

Metallographic examination of milled specimens revealed very little evidence of selective attack; the most severe case being a 0.0002-inch-deep pit at an inclusion. The surface smoothness of the chemically milled areas were good and were generally less than 35 microinches rms and were as low as 14 microinches rms.

Stearns (Ref. 108) indicated that chrome-alloy steels such as H-11 were successfully chemical milled for applications such as missile closures and internal airframe structural members. Uniform etch rates were obtained for these materials in both the annealed and heat-treat conditions; surface smoothnesses of 63 microinches rms or better were readily obtained. A 375 F bake for removal of absorbed gases, e.g., H_2, was generally recommended for the heat-treated materials. Baking of the PH 15-7 Mo alloy after chemical milling was also recommended.

Although generalized comments are frequently made regarding the absence of intergranular attack (IGA), selective etching, or pitting during chemical milling, nonuniform dissolution can and does occur with some materials. Nonuniform dissolution may be the result of not having the "right" combination of etchant-composition and milling-operating conditions to match the particular chemistry and microstructure of the alloy.

Table XXXIV provides information that might be useful for approximating the extent of loss of fatigue strength that may occur with steel alloys because of selective etching or intergranular attack (Ref. 109).

René 41 and Hastelloy X both lost about 15 percent of their fatigue strength due to slight intergranular attack that occurred during chemical milling. There was no intergranular attack on the A-286 material, and no apparent loss of fatigue strength. Although René 41 and Hastelloy X are nickel-base alloys, somewhat similar behavior in fatigue properties might be expected with the stainless and alloy steels if intergranular attack or nonuniform dissolution of similar depths were to occur during chemical milling.

TABLE XXXIV. EFFECTS OF CHEMICAL MILLING ON FATIGUE AND HARDNESS PROPERTIES (REF. 109)

Alloy	Condition[(a)]	Hardness, Rockwell B	Depth of Intergranular Attack (IGA), in.	Endurance Limit, psi
A-286	Parent metal	72	--	~30,000
	Chemically milled	78	None	~30,000
Hastelloy X	Parent metal	92	--	~38,000
	Chemically milled	88	0.0006	~32,500
René 41	Parent metal	99	--	~47,500
	Chemically milled	93	0.0004	~40,000
321 stainless steel	Parent material	62[(b)]	--	~28,000[(b)]
	Chemically milled	83[(b)]	None	~45,500[(b)]

(a) The parent-metal control specimens were made from sheet in the as-received condition; about 20 mils were removed from each side of the sheet specimens by chemical milling.

(b) These fatigue values were considered questionable because of difficulties in getting adequate sized specimens and representative materials (note hardness values) for the tests. The authors indicated that little difference in fatigue strength would be expected between the unmilled and chemical milled 321 stainless steel since there was no IGA.

No significant difference in the hardness values (see Table XXXIV) between the parent and chemically milled materials was observed [see Table XXXIV, Footnote (b) for comments on the 321 stainless steel material].

Westland Aircraft Ltd. (Ref. 110) carried out reverse-bend tests and sustained-load tests on three low-alloy steel sheet materials; 1Cr-Mo [RS. 130 (SAE 4130 type)], 3Cr-Mo-V [RS. 140], and 5Cr-Mo-V [H. 50] in various processed conditions. The steels were heat treated to 176,000, 206,000, and 242,000 psi, respectively, and chemically milled in acid etching solutions developed by Bristol Aerojet Ltd. All three steels showed the lowest fatigue properties in the as-received condition, intermediate properties after machining and grinding, and the highest properties after chemical contouring. The high properties after chemical contouring were sometimes, but not always, due to removal of a decarburized surface layer. Also, chemical milling caused no failures under sustained load at high proportions of the notched tensile strength.

Some of the examples cited above indicate the importance of developing etchant systems and operating procedures that will provide good uniform dissolution of workpieces and smooth surface finishes. In some instances where nonuniform dissolution has occurred and part performance might be adversely affected, mechanical finishing methods might be employed to remove the thin detrimental or rough surface layer. These supplemental operations add to production costs and would best be avoided by development of better chemical-milling etchants and techniques to obtain parts with good surface properties.

HYDROGEN PICKUP DURING CHEMICAL MILLING

Some high-strength steels are susceptible to hydrogen pickup during chemical milling. Factors governing the amount of hydrogen pickup include: composition and metallurgical structure of the steel alloy, etchant composition and temperature, and etching time.

The susceptibility of various steels to hydrogen embrittlement during chemical milling was studied by Jones (Ref. 111). The six steels investigated together with the hardness values are given below:

(1) 4340 steel, R_C 52

(2) 431 martensitic stainless steel, R_C 40

(3) AM-350 semiaustenitic precipitation hardenable stainless steel, R_C 45

(4) & (5) 301 and AM-355 stainless steels cold worked to high strengths; 301 R_C 42, AM-355 R_C 54

(6) A-286 austenitic precipitation-hardenable stainless steel, R_C 20

The etchant-bath composition was as follows:

Hydrochloric acid: 15 volume percent

Nitric acid: 17 volume percent

Phosphoric acid: 31 volume percent

Water: 37 volume per cent

Dissolved iron: 4 g/l.

Bath temperature was 140 F, and the etch rates were about 1.0 mil/ min. Susceptibility to hydrogen embrittlement was evaluated by means of a bend test in which bending of the specimen was performed as a free end-loaded column at various constant-strain rates. This test had been shown to be suitable for investigation of hydrogen embrittlement of sheet materials.

Of the six steels investigated, only the high-strength 4340 steel and the 301 cold-worked stainless steel were embrittled by the chemical-milling process. Although most of the other steels were similar in structure, and of equal or greater tensile strength, they were not measurably embrittled by hydrogen pickup as evaluated by the constant-strain-rate bend test. The pronounced embrittlement of the 301 stainless steel was attributed to the conversion of the relatively unstable austenite to a low-carbon martensite by the severe cold working (rolling) the steel received.

The original ductility of the 4340 steel was restored by holding it at room temperature between 8 and 33 hours (more precise times were not determined). Substantial recovery of ductility of the 301 stainless was achieved by baking at 400 F for 4 hours. Longer baking at 400 F for 8 hours or baking for 4-1/2 hours at 500 F further decreased embrittlement, but again did not eliminate it completely. Longer baking treatments or vacuum degassing, which would most likely restore ductility, were not evaluated.

In other later work carried out at Convair (Ref. 107), sustained-load notched tensile and bend tests showed no evidence of hydrogen embrittlement due to chemical milling either for Type 301 EH or Type 310 EH stainless steels.

The work discussed above indicates that hydrogen embrittlement can be a problem in the chemical milling of some steel alloys. In general, a baking treatment for 2 to 4 hours at 400 ± 25 F is sufficient to restore ductility to most steel alloys. Adequate testing to determine the need for embrittlement relief and also on the effectiveness of relief treatments on chemically milled steel alloys should be carried out.

SUMMARY

Chemical milling is being used successfully and economically to produce a large variety of stainless and alloy steel parts for aircraft, space-vehicle, and other applications. Considerable impetus to chemical milling of steel alloys may result from the Supersonic Transport Development program.

The use of chemical milling for fabricating alloy steels and other high-strength, high-temperature metals and alloys is expected to increase markedly in the immediate future as better etchants, better maskants, and better overall chemical-milling procedures are evolved.

ELECTRIC-DISCHARGE MACHINING (EDM)

EDM PROCESS

Introduction. The practical development of the electric-discharge-machining (EDM) process by Soviet engineers goes back about 30 years. However, much of the more productive research and development work has been carried out during the past 10 years in the United States and abroad. During this period great advances have been made in machine design, power supplies, electrode-tool materials, etc., all of which have contributed to the establishment of EDM in industry as one of the most utilized of the nonmechanical machining processes.

Process Principles. The EDM process can be described as the shaping of parts by the controlled erosion or removal of metal by rapidly recurring spark discharges striking the workpiece surface. There is, as yet, no universally accepted theory for the exact mechanism of metal removal by EDM. Presentation and detailed discussion of various theories, together with bibliographies of articles on EDM, are given in References 112, 113, and 114.

It is rather generally accepted that erosion or metal removal is brought about by melting and possibly by some vaporization of the metal. A spark discharge will occur when the voltage difference across the gap between the tool electrode and the workpiece electrode becomes large enough to break down or ionize the dielectric fluid and make it act as an electrically conductive channel.

For example, when the voltage between two electrodes separated by a gap of about 0.001 inch containing a dielectric fluid, e.g., hydrocarbon oil, reaches about 70 volts, the dielectric becomes ionized and a discharge occurs (Ref. 113). At this time a flood of electrons, which constitutes the current pulse or discharge, flows through the narrow ionized channel formed in the dielectric. The initial breakdown is assisted by microscopic foreign particles in the dielectric fluid. The electrons striking the workpiece change their kinetic energy into thermal energy. The heat produced causes surface temperatures to rise above the melting point, resulting in the formation of a liquid phase and, possibly, some vapor phase and ions. The melted or vaporized metal particles are violently blasted away or ejected by the impact of the discharge. As the great flow of electrons occurs, the voltage between the tool and workpiece drops to about 20 volts, which is low enough to stop electron flow. The ionized channel collapses, the surrounding dielectric fluid takes its place, and the cycle is completed. The time required to accomplish ionization is about 1 microsecond.

Not all of the molten metal is ejected; craters are formed on both the tool and the workpiece, the smaller craters are normally on the tool. Metal that is ejected from the molten puddle at the discharge column is rapidly quenched by the dielectric fluid into small spherical balls (Refs. 113,114).

The size of the crater formed is determined by the amount of charge transferred. Therefore, it is advantageous to transfer the charge in the shortest possible time in order to allow minimum thermal conduction into the body of the work, while at the same time melting the maximum amount of metal. The transfer of a large amount of charge per discharge produces large craters and rough finishes, whereas a small amount of charge per discharge results in small craters and smoother finishes.

The spark-discharge phenomenon described above can be used to machine metal parts because each discharge removes a tiny amount of material. The discharges occurring at those points on the tool surface that are closest to the workpiece surface can be made to occur at frequencies of about 10,000 to 500,000 times per second. Thus, over a period of time, the rapidly occurring discharges will erode the workpiece in such a manner that the tool shape can be reproduced in the workpiece with an accurately predicted overcut.

Equipment.

Machines and Power Packs. The general equipment requirements for an electric-discharge-machining operation, shown schematically in Figure 29, are as follows:

(1) A machine to hold a shaped tool and workpiece accurately positioned to one another

(2) A power pack supplying a readily controlled high-frequency, pulsating direct current

(3) A servomechanism to maintain accurately the desired gap between the tool electrode and the workpiece

(4) A system for supplying dielectric fluid to the machining zone, flushing away the eroded particles, and removing the particles from the fluid.

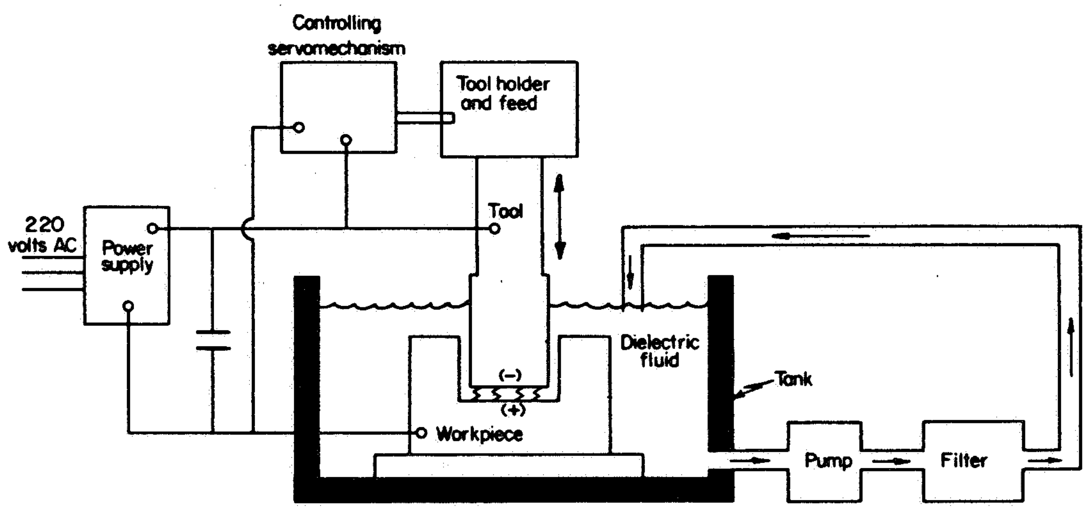


FIGURE 29. SCHEMATIC OF A TYPICAL EDM UNIT

A typical heavy-duty, general-purpose EDM installation is shown in Figure 30 (Ref. 115). The EDM machine is at the right, while the power-supply unit is at the left. The electrode-tool holder and servomechanism are at the top center; the workpieces are positioned on the worktable inside the dielectric tank. The dielectric pumping and filtering equipment can be seen at the right rear of the EDM machine.

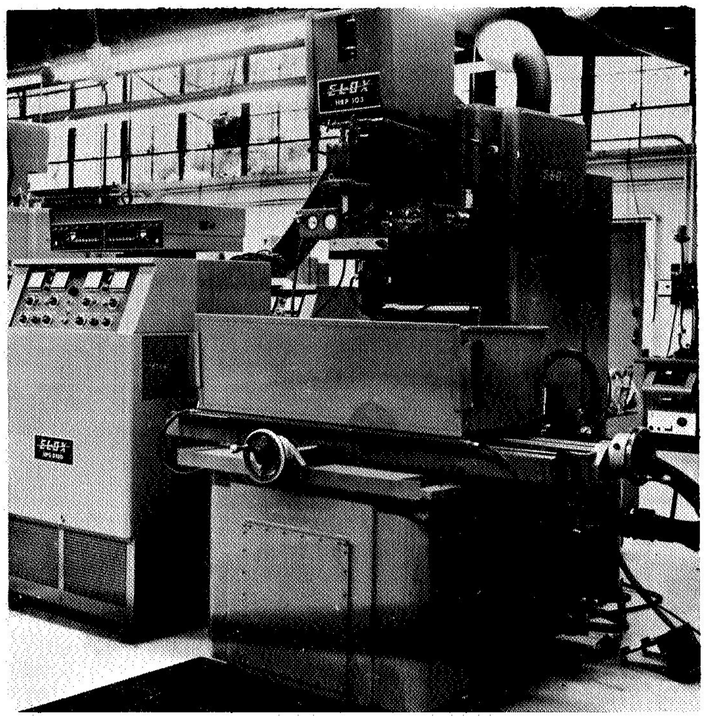


FIGURE 30. TYPICAL ELECTRICAL-DISCHARGE-MACHINING INSTALLATION (REF. 115)

Courtesy of the Elox Corporation of Michigan, Troy, Michigan.

Power packs come in a variety of sizes and utilize a variety of basic circuits to supply pulsating direct current to the electric-discharge machines. According to a recent The Iron Age survey (Ref. 116), the most popular size of electrical unit used today is in the 15 to 30-ampere range. The present trend, however, seems to be in the direction of larger units, for example those in the 40 to 100-ampere class. These larger units often have split- or dual-current-supply features, which permit them to supply current simultaneously to two electrodes (split) or to two separate EDM machines (dual), etc.

Power packs with capacities of 300 and 400 amperes now are available commercially, and larger units are in the planning or design stages. Although much of the EDM work is being carried out at voltages in the range of about 30 to 100 volts, the newer units are generally being supplied with higher maximum voltage outputs, e.g., 200 to 400 volts. Machining frequencies for most EDM units range from about 5,000 to 300,000 cycles per second and higher.

Generally each power-pack unit will provide many combinations of currents, voltages, capacitances, and frequencies to use in achieving a wide range of metal-removal rates and surface finishes. Detailed descriptions of commercially available power packs together with their ratings and capabilities can be readily obtained from EDM-equipment makers.

Servomechanism. The purpose of the servomechanism is to control the feed of the shaped tool into the workpiece so that a predetermined gap is maintained and efficient machining can take place. The servomechanism receives a voltage signal from the machining gap; this voltage, which is gap dependent, is then compared with a specific reference voltage. The servomechanism, acting in response to the voltage across the gap, will either advance or retract the tool so that machining will proceed at a specified voltage. The servomechanism will also retract the tool if a shorted condition occurs, allow the dielectric fluid to flush out the metallic debris causing the short, and then return the tool to the normal machining gap.

Generally, operating gaps between the tool and workpiece range from about 0.0002 inch to about 0.015 inch. The smaller gaps are usually employed for finishing-type work with smooth surfaces, whereas the larger gaps are used for roughing work carried out at higher metal-removal rates.

Dielectric Fluid System. The EDM fluid must act as an insulator until sufficient voltage is applied across the gap to make it break down and become a conductor for the spark discharge. The fluid must then quickly heal itself and again become an insulator so that electrical energy can immediately be built up to produce the next spark discharge. In addition to confining the spark to a small area, the dielectric fluid serves as the medium for removing the metallic debris.

Although not shown in Figure 29, the dielectric fluid is generally made to flow through small holes or openings in either the tool or the workpiece. In this manner, effective flushing out of debris and also cooling of the spark-discharge zone and electrodes can be achieved. Dielectric pumping pressures of about 10 to 100 psi are used, with the more normal range being about 10 to 40 psi. Vacuum or suction are sometimes employed to remove the dielectric fluid and debris from the work zone. The dielectric fluid is continuously filtered in order to provide a steady flow of a clean fluid to the cutting site.

Hydrocarbon fluids possess good dielectric properties for EDM use and are generally employed. The fluids include heavy transformer oils, paraffin oils, light oils, kerosenes, and mixtures thereof (Ref. 117). More recently special silicone oils have been used for EDM (Ref. 118). Berghausen, et al. (Ref. 113) have reported experimental work that indicated that a mixture consisting essentially of triethylene glycol, water, and monoethyl ether of ethylene glycol, performed better in the machining of steel than conventional hydrocarbon fluids when used with metallic electrodes. Higher machining rates, lower tool wear, and improved discharge initiation and stability were noted. The polar fluids performed as well as the hydrocarbon fluids when carbon electrodes were used.

Since dielectric fluids play a vital role in overall EDM performance, they should be carefully selected. Their performance under variable operating conditions with different electrode materials should be carefully noted to permit good EDM results. Data and recommendations on dielectric fluids are usually available from EDM-equipment manufacturers.

Electrode Materials. The electrode in EDM closely reproduces its own configuration in the workpiece, and in a sense can be considered comparable with a cutting tool in conventional machining.

Desirable features of a good electrode material are:

(1) High metal-removal rate, i.e., from a workpiece

(2) Low wear

(3) Ability to produce accurate workpieces with good surface finishes

(4) Good machinability or fabrication properties

(5) Low cost.

Selection of the electrode material is made by considering all the above factors and how they apply to a particular operation or application. The electrode costs can be a major or significant part of the overall EDM costs.

During the EDM operation, as the tool wears the tool shape changes, so in many instances the completion of a job may require use of several similarly shaped tools or of progressively larger tools. The initial electrodes are generally classed as roughing electrodes, whereas the later ones are considered finishing electrodes. Differences in spark gap (overcut) between tool and workpiece at various EDM machine settings must be considered to properly size tool electrodes.

Since wear is always present with EDM electrodes, efficient and relatively inexpensive methods of fabricating accurate tool shapes are very desirable from an economy viewpoint. Electrodes are generally machined or ground using conventional machining techniques. In addition, other methods such as forging, casting, sintering of powder forms, electroforming, spraying, etc., are frequently employed for electrode fabrication.

Among the more widely used EDM tool materials are: brass, copper, carbon or graphite, copper-tungsten, silver-tungsten, zinc-tin, steel, and proprietary materials.

Some performance data on various electrode materials for machining stainless and alloy steels are presented on pages 157 and 161.

Advantages and Limitations of EDM. Some unique features or advantages of the EDM process are:

(1) Ability to generate complex configurations with single-axis tool travel

(2) Ability to provide burr-free machining

(3) Ability to cut high-strength materials

(4) No tool-to-workpiece contact; this permits machining of fragile parts or structures

(5) Good machining-gap control; this contributes to attainment of part accuracy and to holding of close-tolerance ranges on parts.

These desirable features of EDM are utilized for machining or fabricating parts that are difficult to make by conventional machining methods because of their shape or because of the hardness or toughness of the metal or alloys. The greatest single application of EDM is the production of or finish machining of dies of all sorts. Other important uses of EDM are to drill small-diameter holes, multiple-hole drilling, production of irregular-shaped holes or slots, blanking of parts from sheets. EDM's ability to machine dies or parts in their fully hardened condition is an important feature for the above applications.

EDM is particularly suited for resinking of work or washed-out dies. Cast zinc-tin electrodes, which can be easily and inexpensively made, are often used for this application. Substantial savings result over resinking by conventional machining methods.

Two major limitations of the EDM process are its relatively low metal-removal rates and its electrode wear. The electrode tool wear can be a costly factor that, coupled with the relatively low metal-removal rate, will determine whether EDM can be used economically for various machining jobs. However, EDM's ability to produce intricately shaped parts or machine materials that cannot be readily done by other methods may override the above limitations. Considerable progress in overcoming the limitations of low metal-removal rates and electrode wear has been made in the last 5 years by development of improved power supplies, electrode materials, and operating procedures.

OPERATING AND PERFORMANCE DATA FOR EDM OF STAINLESS AND ALLOY STEELS

Data and results taken from the comprehensive study by Berghausen, et al. (Ref. 113) on the machining of stainless and alloy steels, using some of the more efficient tool material (e.g., zinc, brass, copper, and carbon), are given in Table XXXV. Details of the EDM operating conditions employed, together with definitions of the various performance-criteria terms used, are given in the footnotes to Table XXXV. The results of these studies are in general agreement with results obtained by others for machining the stainless and alloy steels.

Substantially higher metal-removal rates (about two to four times greater) were obtained with carbon than with the other tool materials; brass was second; zinc was third; and copper last. For example, the metal-removal rate for carbon tool steel using a carbon electrode was 0.001 cu in./amp min; with a current of 10 amperes for 1 hour, this corresponds to the removal of 0.6 cu in. of metal; at 100 amperes the amount would be about 6 cu in./hr.

Zinc and carbon exhibited the best wear properties and were closely comparable. The average work/tool-wear ratios (based on data in the table for machining the various alloys) were as follows: zinc - 4.8, carbon - 4.4, copper - 3.1, and brass - 2.1.

TABLE XXXV. OPERATING AND PERFORMANCE DATA FOR EDM OF STAINLESS AND ALLOY STEELS USING VARIOUS TOOL MATERIALS[a] (REF. 113)

Tool Material	Item	Workpiece Material						
		Iron-Base Alloy, Thermold J	Iron-Base Stainless Alloy, 17-7 PH	Iron-Base Stainless Alloy, 17-4 Mo	E 4340 Alloy Steel	AISI 1018 Steel	Carbon Tool Steel	Hardened Carbon Tool Steel (R_C-65)
Zinc	Workpiece metal-removal rate,[b] (cu in. /amp min) x 10^4	2.24	1.80	1.73	2.18	3.10	3.46	3.76
	Workpiece volume removed/discharge,[b] cu in. x 10^9	3.22	2.82	2.15	2.81	5.51	5.71	5.58
	Work/tool-wear ratio[c]	4.14	4.61	4.56	4.65	4.52	5.05	6.30
	Machinability[d], (discharges/min) x 10^{-5}	6.98	5.74	5.62	8.56	5.67	6.06	6.76
	Overcut[e], in. x 10^3	4.0	4.8	4.2	3.6	5.0	4.0	4.0
	Surface roughness, rms microinches	N.D.	150	N.D.	N.D.	200	200	190
Yellow Brass (65 Cu-35 Zn)	Workpiece metal-removal rate, (cu in. /amp min) x 10^4	2.83	2.62	2.46	3.69	2.86	2.98	3.22
	Workpiece volume removed/discharge, cu in. x 10^9	3.60	4.08	3.29	505	3.74	4.35	4.79
	Work/tool-wear ratio	1.67	2.05	1.95	2.51	2.07	2.15	2.46
	Machinability, (discharges/min) x 10^{-5}	9.43	7.07	8.89	3.77	7.64	6.84	6.71
	Overcut, in. x 10^3	3.4	3.1	2.7	3.5	3.5	3.1	3.0
	Surface roughness, rms microinches	N.D.	195	N.D.	N.D.	175	190	190
Copper	Workpiece metal-removal rate, (cu in. /amp min) x 10^4	1.37	1.38	1.47	1.11	1.59	2.44	2.51
	Workpiece volume removed/discharge, cu in. x 10^9	2.85	2.31	2.40	1.90	2.96	4.24	4.38
	Work/tool-wear ratio	3.51	2.87	2.53	2.76	2.91	3.57	3.36
	Machinability, (discharges/min) x 10^{-5}	5.79	6.88	7.07	7.00	5.67	5.74	5.72
	Overcut, in. x 10^3	2.7	2.9	3.0	4.3	3.0	3.0	3.0
	Surface roughness, rms microinches	N.D.	140	N.D.	N.D.	160	180	180

TABLE XXXV. (Continued)

Tool Material	Item	Workpiece Material: Iron-Base Alloy, Thermold J	Iron-Base Stainless Alloy, 17-7 PH	Iron-Base Stainless Alloy, 17-4 Mo	E 4340 Alloy Steel	AISI 1018 Steel	Carbon Tool Steel	Hardened Carbon Tool Steel (R_C-65)
Carbon (f)	Workpiece metal-removal rate (cu in./amp min) x 10^4	7.56	7.33	6.18	6.98	8.60	10.0	10.9
	Workpiece volume removed/discharge, cu in. x 10^9	8.67	7.78	7.07	7.11	11.2	11.5	13.4
	Work/tool-wear ratio	4.18	3.83	3.54	4.58	4.90	4.05	6.05
	Machinability, (discharges/min) x 10^{-5}	8.70	9.46	8.78	8.89	1.68	8.71	8.17
	Overcut, in. x 10^3	2.5	1.0	2.5	2.9	3.0	1.4	1.5
	Surface roughness, rms microinches	N.D.	220	N	N	260	240	250

(a) All data were obtained on a Cincinnati No. 1 Electrojet EDM machine using an experimental static impulse generator power supply. All tests were standardized with a peak-to-peak open circuit voltage of 70 volts; on time of 30 microseconds, off time of 30 microseconds, and a series capacitance of 30 microfarads giving a frequency of 10^6 cycles per minute. The tools were 0.5 inch in diameter, with a 0.104-inch-diameter center flow hole. A light hydrocarbon oil was used as the dielectric fluid; during machining the fluid was continously circulated, filtered, and held at a constant pressure of 10 psi. Whenever possible a machining current of 10 amperes was maintained and the duration of each cut, whenever possible, was 10 minutes.

(b) Metal-removal rates for both the workpiece and tool were calculated from weight losses, densities, duration of cut, and average current during machining.

(c) Wear ratios (i.e., volume of workpiece removed to volume of tool removed) were calculated from weight losses and densities.

(d) Machinability was measured by counting the number of current pulses in the discharge circuit during the machining operation.

(e) Overcut is the difference in radii between a round tool and the hole produced by that tool.

(f) A commercial carbon electrode was used.

The general overcut ranges for the work reported in Table XXXV for the various tool materials against the stainless and alloy steel workpieces were as follows:

Carbon: 0.0015-0.0030 inch

Copper: 0.0027-0.0030 inch

Zinc: 0.0040-0.0050 inch

Yellow Brass: 0.0030-0.0035 inch.

The surface roughness on the alloy steels were about the same for all three metallic electrode materials, ranging from about 150 to 200 microinches rms. With the carbon material (which had the substantially higher metal-removal rates) the surface roughnesses were higher and ranged from about 220 to 260 rms microinches.

The data above indicate that the general overall performance of the carbon material was the best of the four tool materials evaluated for EDM of stainless and alloy steels. It showed superior metal-removal rates, good wear properties, good machinability, and was roughly comparable with the metallic materials with respect to overcut and slightly inferior with respect to surface roughness.

It should be indicated that because of the large number of variables involved and their complex interdependent relationships the same results as given in Table XXXV would not necessarily be obtained under different EDM operating conditions. However, the data given in Table XXXV are believed to be generally representative of results to be obtained in EDM of the stainless and alloy steels.

In their study, which included other metal workpiece and tool materials besides those cited in Table XXXV, Berghausen, et al. (Ref. 113) found that metal-removal rates could be expressed as functions of the thermal properties of the electrode materials and that melting point, heat of fusion, and heat and electrical conductivity were important factors in EDM performance. They showed that

(1) Average metal-removal rates from the workpiece were inversely proportional to the 5/4 power of the melting point of the workpiece material. The proportionality constant depends upon tool material, dielectric fluid, machine tool, power supply, and servo system.

(2) Average metal-removal rates from the tool were inversely proportional to the 9/4 power of the melting point of the tool material. The proportionality constant is dependent on the workpiece material and the other factors mentioned in (1) above.

(3) Wear ratios (volume workpiece/volume tool) were inversely proportional to the 7/3 power of the ratio of their respective melting points. The constant of proportionality depends upon the dielectric fluid, machine tool, power supply, and servomechanism.

Typical performance data taken from industrial case histories (Ref. 116) for carrying out various types of EDM operations on a variety of stainless and alloy steels using different tool materials are given in Table XXXVI. The EDM operations covered include: machining blanking dies, forging dies, extrusion dies; cavity sinking; multiple-hole drilling, and drilling of irregular-shaped holes. Data are presented on tolerances, surface roughnesses, and metal-removal rates for machining with various workpiece/electrode combinations using different capacity power supplies.

The closest tolerances cited were ±0.0002 inch; for most jobs the tolerances ranged from about ±0.001 to ±0.003 inch; for forging-die and cavity-sinking work the tolerances were about ±0.005 inch. Surface roughnesses ranged from 5 to 250 microinches rms, with the bulk of the work falling in the range of about 20 to 80 microinches rms. As indicated earlier, surface roughnesses of 10 microinches rms and less can be obtained provided one is willing to machine at low metal-removal rates by using low-energy discharges at high frequencies. The fineness of the surface finish to strive for will be determined by the end-use surface requirements of the part or product, or by some compromise between surface roughness and the economy of machining at various metal-removal rates.

The melting and resolidification process that occurs because of the thermal action of EDM can change the hardness or physical properties of the surface so that they differ from those of the bulk metal. The depth of the resolidified layer may range from about 0.0001 to about 0.003 inch; and depends greatly on the EDM operating conditions. In some instances cracks may occur, but they are generally confined to the thin surface layer. The depth of the resolidified surface layer can be greatly minimized by operation at low power levels at high frequencies, such as is done in finishing-type

TABLE XXXVI. TYPICAL PERFORMANCE CHARACTERISTICS TAKEN FROM CASE HISTORIES FOR VARIOUS EDM OPERATIONS ON STEEL ALLOYS[a]

EDM Operation	Workpiece Material	Tool Material	Electrical Unit Current, amperes	Workpiece Removal Rate[b], cu in. /hr	Tolerances, in.	Surface Roughness, microinches rms
Machining blanking dies	Tool steel	Brass	31-40	0.5	±0.001	32-62
	Tool steel (0-2)	Graphite	41-60, 64-100	0.5	±0.0005	32
	Tool steel	Graphite and brass	15-30	1.5	0.0005	8
	Tool steel	Copper-tungsten, brass	15-30	0.046 cu in. / hr/amp	±0.0002	30-50
	Tool steel (D-2)	Graphite	15-30	0.014 cu in. / hr/amp	--	100-250
	Hardened steel	Graphite	50-60	0.7	±0.0002	50-60
	Hardened steel	Brass, copper	15-30	0.4 to 0.5	±0.005	170
	High C-high Cr steel	Graphite	15-30	0.2 to 0.4	±0.0003	50
Machining forging dies	Die steel	Graphite	100-300	8	±0.005	125
	Hot-work steel	Brass	15-30	1.3	±0.005	100
	1021 steel	Brass, copper	15-30	0.4 to 0.5	±0.005	170
	H-15 steel	Sintered copper	31-40	2.5	±0.005	125
Machining extrusion dies	H-11 steel	Graphite	31-40	0.060	±0.001	80
	H-13 steel	Graphite	41-60	1 to 2	±0.002	20-40
Drilling burr-free and non-circular holes	Stainless	Graphite	41-60	0.125	±0.002	125
	Stainless	Copper-tungsten	41-60	0.024	±0.001	40
	4340, T-1, and 17-4 PH steels	Silver-tungsten	41-60	0.029 cu in. / hr/amp	±0.0005	64
	Mild steel	Graphite	31-40	0.25	±0.002	150
Multiple-hole drilling	Hardened steel	Brass	15-30	0.05	±0.0005	50
	4140 steel	Graphite	100-300	0.015 cu in. / hr/amp	±0.001	50
	Stainless	Graphite	41-60	0.060	±0.002	63
Machining cavities	Tool steel	Graphite, brass	15-30	1.5	±0.005	5
	Tool steel (H-12)	Graphite	41-60	1 to 2	±0.010	20-40
	Die steel	Graphite	100-300	2.5	±0.005	50
	Stainless	Copper-tungsten	41-60	0.048	±0.001	63

(a) Data are from the results of a survey made by The Iron Age (Ref. 116). The data represent typical results reported by respondees to the survey.
(b) Metal-removal rates are expressed as cu in. /hr, unless otherwise indicated.

operations. The thin, hard surface layers are not necessarily objectionable or detrimental; in fact for many tool and die applications increased wear resistance has been attributed to the hardened layers. However, for applications where the layer is undesirable, as for stressed parts subjected to vibratory loading, the layer should be removed. This can be done by finish grinding, lapping, chemical etching, or electropolishing.

Figure 31 shows EDM-produced forging dies for making double thimble eye-pole line hardware (Ref. 115). One blocker and two finishing impressions were produced in each die half from solid die blocks. The holes for dielectric flow through the electrode to the EDM zone and out can be seen in Figure 31. The time and costs for producing both die halves by conventional methods were 80 hours (including 15 to 20 hours benching time) and $800, respectively, as opposed to 11 hours and $410 for EDM. The $410 figure includes costs of $300 for electrodes.

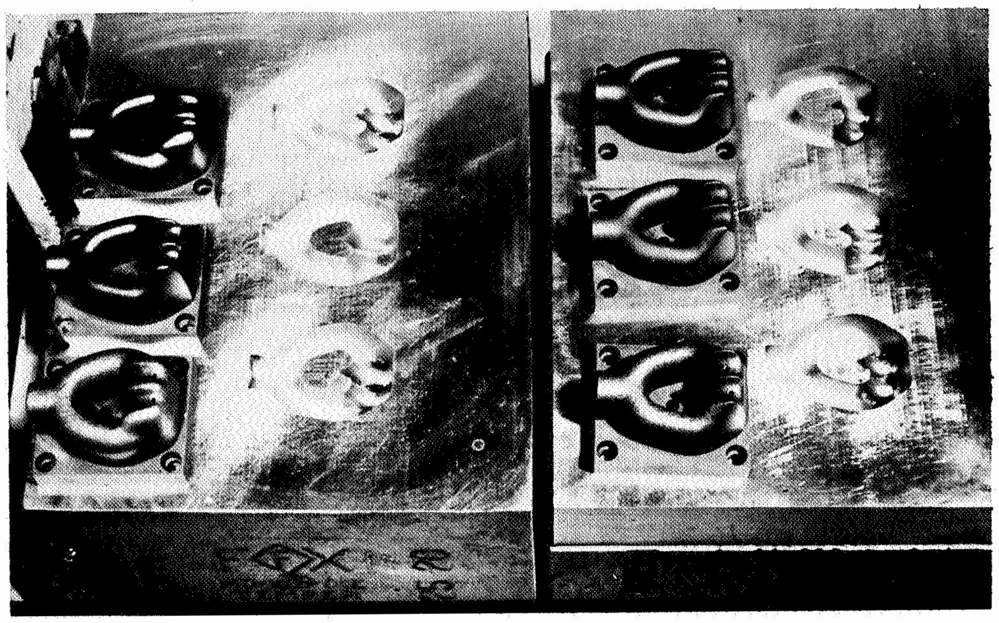


FIGURE 31. EDM-PROCESSED FORGING DIES (REF. 115)

Courtesy of the Elox Corporation of Michigan, Troy, Michigan.

SUMMARY

Electric-discharge machining has become well established for machining or shaping parts that cannot be produced readily by conventional methods, because of the complex shapes involved or

because of the hardness or toughness of the materials, and where high rates of metal removal are not critical. Die and tool making constitute the major uses of the EDM process at this time.

EDM, which is already widely employed in industry, is expected to be even more extensively used for machining hard steels and other tough alloy parts during the years to come. It is also expected that production uses of EDM will increase in the electronics, aerospace, and other industries for machining complex shaped or fine-detailed parts, especially those made of the difficult-to-machine metals. The EDM process is suited for automation for production purposes.

Research and development work aimed at increased metal-removal rates, better surface finishes, and lower tool wear is expected to make the overall EDM operation more efficient and economically more attractive to use in the years ahead. Significant improvements in EDM performances have been achieved within the last 5 to 10 years by the development of new or improved power supplies, electrode-tool materials, dielectrics, and operating procedures, and more progress can be expected in the years to come.

CONCLUSIONS AND RECOMMENDATIONS

The metal-removal difficulties of aerospace materials usually stem from various combinations of high strength, work-hardening rates, and thermal diffusivity. The tool-life problems involved may originate from excessive cutting temperatures, a severe abrading or welding action of the chip, or a combination of these conditions. The relatively low metal-removal rates characteristic of these materials result from the low cutting speeds used to minimize cutting temperatures, and the lighter feeds and depths of cut needed to prevent overloading the tool.

These problems suggest the need for continued development of cutting-tool materials, and an accelerated program to produce better machine tools. A U. S. Air Force research program on cutting-tool materials is now in progress with the overall objective of producing improved versions of high-speed steels, cobalt-cast alloys, and cemented carbides. The machine-tool industry is continually unveiling new models of high-quality machine tools with increased emphasis on rigidity and versatility, but more needs to be done.

The general situation today is that many existing lathes do not possess broad enough spindle speed ranges to cover the low speeds needed for metals of low machinability. These low speeds not only should be provided, but the entire speed range of the lathe should be adjustable in steps of 20 per cent or less. One approach in new lathes is to use continuously variable-speed drives. Rigidity, dimensional accuracy, and flexibility are features that are also being emphasized.

The situation for grinders parallels that for lathes. Grinders should possess the necessary adjustment to reduce spindle speeds to values needed for high-strength materials. Grinders should also provide automatic wheel-wear compensation to improve dimensional control when softer grinding wheels are used. A need also exists for greater rigidity in the spindle system along with wheel-balancing devices.

Profile machining of parts to close tolerances using numerically controlled profiling machines is expected to increase greatly in the near future. This means that optimized machining information on specific operations will be needed in suitable form for use by clerks and technicians. This need will become more pressing as the demand for high-strength metals increases and the availability of skilled machinists and machining specialists decreases. Useful data in suitable form simplify the programming of numerically controlled machine tools considerably.

Nonmechanical metal-removing processes are contributing to the metal-removal needs of aerospace materials in special ways. Electrochemical machining, chemical milling, and electric-discharge machining already are handling extremely hard materials and machining situations that are difficult or impossible for conventional machining methods.

Electrochemical machining, already being used in industry, will be used more extensively for machining steel, the so-called tough alloys, and much larger parts. It is readily adaptable for production work and automation, and does not require highly skilled personnel.

Electrochemical machining, however, is not without problems. To help overcome them, fundamentals of electrode design, electrolytic action, fluid flow, and electrolyte composition related to electrochemical machining should be developed further, and the information disseminated to enable more engineers to understand ECM and to realize its potential for more applications. Electrolyte compositions also should be constantly improved and new ones developed toward the goal of good surface finishes.

Chemical milling is being used successfully to remove metal from formed or complex parts, from thin sections, and from large areas. Generally, when uniform dissolution is achieved, chemical milling does not adversely affect mechanical properties. However, nonuniform dissolution can and does occur with some materials due to mismatch among the etchant composition, the operating conditions, and the microstructure of the alloy being milled. Therefore, it is important that further investigation be made into the interrelationship of the above variables. It is equally important to develop improved etchant systems and operating procedures to provide higher metal-removal rates and/or smoother surface finishes. Higher rates will lower production costs.

Electric-discharge machining is well established in industry for machining or shaping parts not readily produced by conventional machining methods. Die and tool making constitutes the major uses. However, the EDM process is also used to produce small-diameter holes, multiple holes, or irregular-shaped holes, and to blank parts from sheet material. It is highly suited for automation for production purposes.

It should be pointed out that the melting and resolidification/quenching action of the EDM process can produce a surface condition or hardness different from that of the underlying layers, as in the case of untempered martensite in high-strength steels. This may be helpful in the case of dies, but could be detrimental where stressed parts or fatigue conditions exist. In some instances the thin surface layer may crack. The hardened or cracked layer should be removed if it is objectionable in any way, for example, in applications in which fatigue-type loading is involved.

Problems of electrode tool wear and low metal-removal rate also exist and may determine whether EDM can be used economically. Research and development work should be continued toward goals of increased metal-removal rates, better surface finishes, and lower tool wear. This research should encompass new or improved power supplies, electrode-tool materials, dielectrics, and operating procedures.

APPENDIX

APPENDIX

CLASSIFICATION OF STEELS AND OTHER ALLOYS

Steels and nonferrous alloys used in high-performance aircraft and missiles can be classified into three main categories as shown in Table XXXVII. The general classes of materials include the high-strength constructional alloy steels, the stainless steel alloys, and certain nonferrous metals and alloys possessing high strength-to-weight ratios, or stable properties. The nonferrous alloys will not be discussed in this report since they are covered in other NASA Technical Memorandums.

A good deal of confusion sometimes surrounds the use of the common term, "high-strength steels". It seems to be used, frequently and indiscriminately, for all classes of steel capable of exceeding the properties of carbon structural steels. Accordingly, the term high-strength constructional alloy steel has been used in this report to include the four classes of high-strength steels based on yield strength as shown in Table XXXVII (Refs. 119-121).

Stainless steel alloys, as a class, are more versatile than the alloy steels. Some stainless grades are capable of attaining ultrahigh strengths, while others are designed to exhibit corrosion resistance and resistance to softening at very high temperatures. Table XXXVII separates these two capabilities and lists the alloys in each category.

Although this report deals only with the ultrahigh-strength steels and the stainless steels, much of the information and data developed could apply to the proprietary groups of high-strength steels as well as to the nickel steels. Separate information on the machining of nickel steels is available in a machining booklet published by The International Nickel Company (Ref. 122).

GENERAL INFORMATION ON ULTRAHIGH-STRENGTH STEELS

The development of ultrahigh strengths in alloy and stainless steels has been the goal of much research in ferrous metallurgy. The usual means of increasing strength in martensitic steels was to increase the alloy content and to lower the tempering temperatures when heat treating (Ref. 9). Precipitation hardening was used for the maraging steels and selected stainless steel compositions. The

TABLE XXXVII. CLASSIFICATION OF STEELS AND OTHER ALLOYS[a]
(REFS. 119-121)

High-Strength Constructional Alloy Steels (Nonstainless Types)	Stainless Steel Alloys	Nonferrous Alloys
Ultrahigh-Strength Steels	**Ultrahigh-Strength Steels**	**Titanium Alloys**
Low-alloy engineering steels	Martensitic stainless steels	Ti-6Al-4V
AISI 4130 types	Type 410	Ti-8Al-1Mo-1V
AISI 4340 types	Type 420	
Medium-alloy die steels	Martensitic PH stainless steels	Nickel-Base Alloys
AISI H-11 types	17-4 PH	Rene 41
AISI H-13 types	Cold-worked austenitic stainless steels	Cobalt-Base Alloys
Low-carbon, high-nickel maraging steels	Type 301	HS-25
18Ni-Co-Mo	Semiaustenitic, PH stainless steels	Refractory Metals
20 Ni	17-7 PH	Molybdenum
25 Ni	AM-350	Tungsten
		Tantalum
		Columbium
High-Strength Nickel Steels	**Special Stainless Steels**	
AISI 2300 types	Ferritic stainless steels	
AISI 2500 types	Type 442	
9% Ni types	Type 446	
High-Strength Proprietary Steels	Austenitic stainless steels	
Tri-Ten	Type 304	
Man-Ten	Type 347	
Extrahigh-strength Proprietary Steels	Stainless steel superalloys	
T-1	Timken 16-25-6	
J Alloy 90	19-9D2	
N-A-Xtra 90	Austenitic, PH stainless steels	
	Discaloy	
	A-286	

(a) Materials covered in this report are contained within the dashed lines shown.

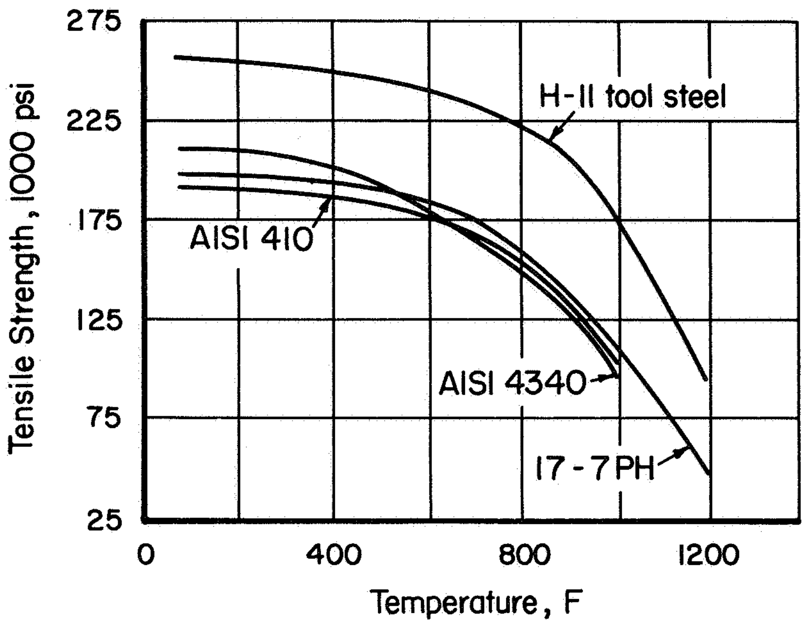
result has been that a range of 150,000 to 250,000 psi in tensile strengths has been realized, and a level as high as 450,000 psi in isolated cases has been reported. Figure 32 illustrates how the tensile strengths of some of these materials vary with temperature (Ref. 123). Additional properties as well as applications are discussed in the following sections dealing with individual classes of steels (Refs. 10,11,124-126).

Low-Alloy and Medium-Alloy Aircraft Steels. Two major groups of steel constitute most of the alloy steels being used in present-day missiles and high-performance aircraft. They include the medium-carbon, low-alloy quenched and tempered engineering steels (AISI 4100 and 4300 series), and the medium-alloy air-hardening die steels (AISI H-11 and H-13 series). Table XXXVIII lists some typical steels in these groups (Refs. 9,121).

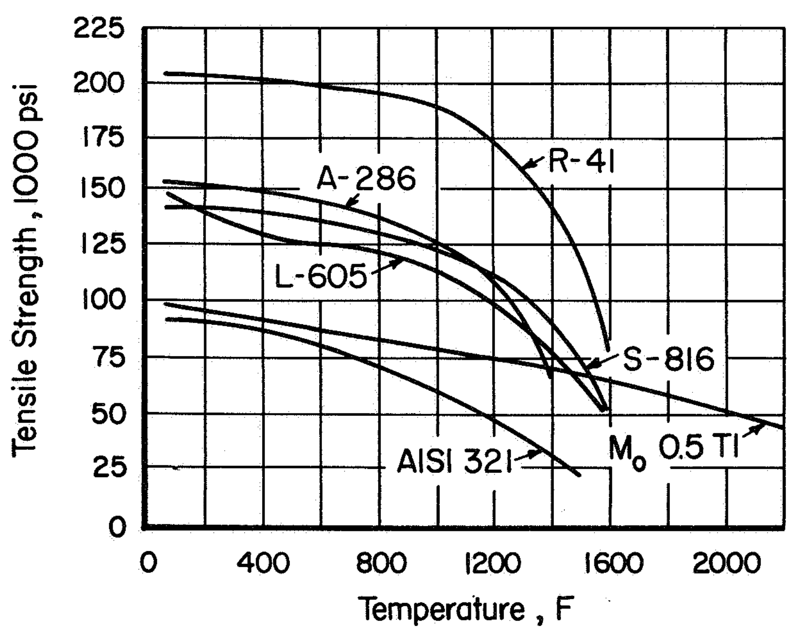
The steels listed in Table XXXVIII have several similarities. High strength is achieved in all of them by heating to temperatures where the austenitic phase is stable, cooling to transform the austenite to martensite, and tempering the martensitic structure to the desired hardness. All are susceptible to decarburization during fabrication and heat treatment. Although the hot-work die steels are slightly more corrosion resistant than are the low-alloy engineering steels, they, too, must be protected during shipment and storage after fabrication. Hydrogen embrittlement is a possibility to be considered in all heat-treated steels that have been pickled or plated. As the strength levels are increased, these steels become increasingly notch sensitive.

Cr-Mo Steels. The low-alloy AISI 4130 steel is the base composition in the Cr-Mo steel family. Increased hardenability over its plain-carbon counterpart, the AISI C-1030 steel, is obtained from chromium and molybdenum additions. Excellent strength-to-weight ratios, and good weldability characterize this group of steels. Consequently, these steels constitute the most important group of steels for aircraft structural assemblies (Refs. 9-11).

Cr-Ni-Mo Steels. The Cr-Ni-Mo group of steels, typified by the AISI 4340 composition, was designed for applications requiring deeper hardening capabilities than would be feasible with the AISI 4130 type steels. This increase in hardenability stems from increases in manganese and molybdenum and from nickel additions.



a. High-Strength Steels



b. High-Temperature Alloys

FIGURE 32. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF HIGH-STRENGTH STEELS AND HIGH-TEMPERATURE ALLOYS

TABLE XXXVIII. EXAMPLES OF LOW-ALLOY AND MEDIUM-ALLOY AIRCRAFT STEELS

	Medium-Carbon Low-Alloy Engineering Steels		Medium-Alloy Die Steels
Alloy type:	Cr-Mo	Cr-Ni-Mo	5Cr-Mo-V Hot-Work Die Steels
Typical analysis:	Cr-0.50 to 0.90 Mo-0.12 to 0.20	Cr-0.50 to 0.80 Ni-1.80 Mo-0.25	Cr-5.00 Mo-1.50 V-0.40-1.00
AISI type:	4100	4300	H-11
Typical heat treatment:	Quench and temper	Quench and temper	Air hardening
	AISI 4130 AISI 4140 (Mod) 17-22-AS	AISI 4340 AMS 6434 D-6-AC	H-11 H-13 Crucible 56 (Peerless 56)
Typical steels and their modifications:	Airsteel X-200 UHS-260 UCX-2 MBMC No. 1	300-M USS Strux Super Tricent HY-Tuf	Crucible 218 Potomac A Potomac M Vascojet 1000 Unimach I Unimach II Dynaflex

AISI 4340 steel has been used for many years by the aircraft industry in landing gears and other critical parts. Because of its widespread use and industry's familiarity with this steel, it has become the standard high-strength steel (Refs. 9-11,124-126).

5Cr-Mo-V Steels. The need for ultrahigh strength along with improved thermal stability has encouraged the use of the 5Cr-Mo-V hot-work die steels in applications other than tools and dies. Steels in this category can achieve room-temperature tensile strengths up to 310,000 psi. These steels will maintain stable properties at temperatures up to 900 or 1000 F for limited periods of time because of their ability to achieve secondary hardening when tempered at 1000 to 1100 F. Consequently, the 5Cr-Mo-V tool steels offer freedom from retained austenite, which, if present, can cause premature failure under load.

Uses for these steels include ultrahigh-strength applications in landing gears, airframes, missile bottles, and high-strength fasteners (Refs. 9,11-13,124,126).

Low-Carbon, High-Nickel Maraging Steels. The development of a group of low-carbon, high-nickel martensitic steels strengthened by a precipitation-hardening mechanism was announced in 1959. They were termed maraging steels because a precipitation-hardening mechanism occurs when the steels are aged in the martensitic condition. A reasonable ductile martensite of moderate strength is first obtained after annealing at 1500 F. The maraging steels can be fabricated in this condition. Ultrahigh strength is then achieved by a simple aging treatment in the vicinity of 900 F.

Three basic compositions have emerged: the 25Ni, the 20Ni, and the 18Ni-Co-Mo maraging steels. Most of the development work is being done on the 18Ni-Cr-Mo maraging steels. These steels have the promise of good fracture toughness at high-strength levels and their heat treatment is favorable for the fabrication of very large boosters (Refs. 14,125,127,128).

GENERAL INFORMATION ON ULTRAHIGH-STRENGTH STAINLESS STEELS

Martensitic and Cold-Worked Austenitic Stainless Steels. Martensitic and austenitic stainless steels require the presence of 11 percent or more of chromium to achieve passivity, and increases in chromium content above that level produce progressive but not proportional increases in corrosion and heat resistance (Ref. 1). Nickel in the austenitic grades imparts increased toughness, ductility, and corrosion resistance to the resulting alloy. Elements like molybdenum, tungsten, and vanadium are sometimes used for special purposes. Sulfur, selenium, or phosphorus are added to some grades to impart free-machining properties (Refs. 15,55,56).

400 Series. The martensitic grades of stainless steel within the 400 series can be hardened to high strengths by heat treatment. These steels are magnetic like normal steels. Furthermore, they possess fairly good resistance to oxidation and fatigue at elevated temperatures, although they are not particularly resistant to rusting and other corrosive actions at room temperature (Refs. 10, 16).

The martensitic stainless steels by virtue of their high-chromium contents possess greater resistance to tempering than either the low-alloy engineering steels or the medium-alloy die steels. Hence, their applications usually involve operating temperatures, or oxidizing conditions somewhat more severe than those that martensitic steels of lower alloy content will tolerate.

In some cases, the utility of the hot-work tool steels and the martensitic stainless steels will overlap, but greater industrial experience with the latter group of steels often favors their use. In aircraft, the martensitic stainless steels are used as forgings for parts such as hydraulic pumps, engine mounts and fittings, compressor blades, and wheels. Missile applications include rocket motor cases, rings, and attachment fittings (Refs. 11,16,126).

300 and 200 Series. The austenitic or 300 series stainless steels contain substantial alloy additions of chromium and nickel. In the case of the 200 series, fairly large amounts of manganese are used to replace part of the nickel. These steels are generally tough and ductile. They cannot be hardened by heat treatment but can be cold worked to high strengths. They also possess good oxidation resistance at elevated temperatures and good corrosion resistance.

One of the more important engineering concepts to emerge in recent years is the use of austenitic stainless steel at high-strength levels (Ref. 73). The ability of the austenitic grades (such as Types 301 or 201) to be temper rolled to high strengths is the underlying reason for using extrahard Type 301 stainless steel as the skin for the Atlas missile. A comparable industrial application is the all-stainless steel trailer van (Refs. 11,73,129). Another important application is the cryogenically formed pressure vessel from Type 301 stainless steel (Ref. 130).

Precipitation-Hardenable Stainless Steels. The precipitation-hardenable or PH stainless steels resemble the regular stainless steels in composition, but strengths are increased by precipitating tiny particles of special elements or compounds in the martensitic or austenitic matrix. By their presence in the metal, these particles help to resist deformation and fracture. Hence, PH stainless steels are good choices where extrahigh strength is needed along with good corrosion resistance (Refs. 10,11,17,18,124,126, 131).

The martensitic types of PH stainless steels, such as 17-4 PH, are austenitic at elevated temperatures but form martensite on cooling to room temperature. These steels are quite similar to the conventional martensitic stainless steels but are capable of precipitation-hardening-type reactions that provide additional strength (Ref. 16).

The semiaustenitic compositions, such as 17-7 PH, are austenitic at elevated temperature and retain this austenitic structure at room temperature in the solution-treated condition. These materials, however, can be hardened by a martensite transformation induced by heat treatment, refrigeration, or cold work. In the solution-treated condition, they behave very much like austenitic stainless steels and very much like martensitic steels when hardened (Refs. 16,19).

Both the martensitic and semiaustenitic grades possess combinations of properties useful for aircraft structural parts and certain nonmilitary applications. Typical applications for both grades are shown in the following tabulation:

Some Applications for PH Stainless Steels

Martensitic Grade	Semiaustenitic Grade
Turbine valves	Airframes
Fasteners	Honeycomb
Valves	Pressure tanks
Valve seats	Leaf springs
Forgings	Coil springs
Instruments	Surgical instruments
Bearings	Bearings

GENERAL INFORMATION ON OTHER STAINLESS STEELS

Another group of stainless steels was designed principally to provide moderate strength with good resistance to softening, particularly between the temperatures of 1000 and 2000 F. This variety includes some ferritic grades of stainless steel, the high-nickel-bearing austenitic stainless steels, the nonheat-treatable stainless steel superalloys, and the austenitic grades of precipitation-hardenable stainless steels.

Ferritic Stainless Steels. The nickel-free ferritic grades of stainless steel containing 11 to 27 percent chromium generally have good corrosion resistance under a variety of conditions. The applications are somewhat more limited than those of the chromium-nickel stainless steels. The resistance of these grades toward corrosion, generally, and toward scaling at high temperatures, in particular, depends directly on their chromium content. Consequently, Type 442 will resist scaling up to 1950 F, and Type 446 can be used as high as 2050 F, although the latter steel has little strength at this temperature.

Some typical applications of Types 442 and 446 include annealing boxes, furnace parts, heat exchangers, valves and fittings, and mufflers.

Austenitic Stainless Steels. The austenitic grades of stainless steel such as Types 304, 321, and 347 are often selected for their versatility of good strength and excellent toughness, as well as for their abilities to resist heat and corrosion (Ref. 1). The higher chromium and nickel-containing alloys seem to perform the best in this regard. Elements like molybdenum, columbium, and titanium are used in several alloys for special purposes. Applications for three important alloys are shown in the following tabulation:

Some Applications for Austenitic Stainless Steels

Type 304	Types 321 and 347
Atomic-reactor equipment	Aircraft exhaust stacks
Heat exchangers	Aircraft manifolds
Valves and fittings	Jet-engine parts
Containers	Firewalls
Chemical-processing equipment	Chemical-processing equipment
Flue liners	Stack liners
Tanks	Pressure vessels

Stainless Steel Superalloys (Refs. 20-22). These materials in general correspond closely to the compositions of austenitic stainless steels. Manganese also has been successfully used as a substitute for part of the nickel in a number of these alloys.

The compositions were designed primarily for applications requiring combinations of high creep and rupture strengths and good resistance to corrosion and oxidation up to 1300 F. The lower alloy compositions, such as 19-9DL, normally are not used at the highest operating temperatures but are somewhat more machinable than the high-alloy grades (Timken 16-25-6).

These alloys cannot be strengthened by normal heat treatment. Instead, they develop their best properties as a result of hot-cold working. This may mean rolling or forging at almost 2000 F and then finish working between 1200 and 1600 F.

This group of alloys have been widely used for rotor forgings, buckets, turbine wheels and blades, supercharger wheels, frames, casings, and afterburner parts.

Austenitic Precipitation-Hardenable Stainless Steel. The austenitic precipitation-hardenable stainless steel alloys, such as A-286, are very similar to the conventional austenitic stainless steels except that the PH stainless alloys can be aged by a precipitation reaction to develop additional strength (Ref. 16). They find important applications in jet engines as shown in the following tabulation:

Some Applications for Austenitic PH Stainless Steels

Jet-engine frames	Jet-engine casings
Supporting rings	Supercharger casings
Fasteners	Turbine wheels
Afterburner parts	Turbine blades

CLASSIFICATIONS, COMPOSITIONS, AND PROPERTIES OF ALLOY AND STAINLESS STEELS

The iron-base alloys covered in this report are categorized generally into the nonstainless alloy steels and stainless steel alloys shown in Table XXXVII. For machining-classification purposes, the categories are subdivided into four subgroups representing the ferritic, martensitic, semiaustenitic, and austenitic types of steel.* The ferritic and martensitic steels are generally considered to be less affected by work hardening, while the semiaustenitic and austenitic stainless steels usually work harden considerably during machining.

It seems reasonable to expect that a series of alloys having similar compositions and properties within a given subgroup should machine similarly. Accordingly, these alloys have been banded together under a key alloy and assigned group letters as shown in previous machining tables. Table XXXIX, utilizing the above scheme, organizes the key alloys according to machinability ratings and subdivisions. Table XL lists the steels governed by each key alloy.

The compositions and properties of these alloy steels and stainless steels are shown in Tables XLI to XLVI inclusive.** Some of the alloys are no longer used, while others are so new, particularly the precipitation-hardenable types, that little machining experience has been obtained. Typical alloys, however, are listed for completeness.

*The terms here are used only in a qualitative sense to differentiate classes of steels based on their hardening response to heat treatment.

**Data in tables taken from References 9-14, 17-21, 23-27, 119, 124-129, 131-137.

TABLE XXXIX. MACHINABILITY GROUP ASSIGNMENTS OF KEY ALLOYS REPRESENTING THE ALLOY AND STAINLESS STEELS IN THIS REPORT

Type of Steel	Line	Group Assignment by Machinability Rating						
		A (70)	B (60/55)	C (50)	D (45/35)	E (30)	F (25/20)	G (10)
Nonstainless Alloy Steels								
Cr-Mo low-alloy steels	1	4130 (A1)	8640 (B1)			4130[a] (E1)		4130[b] (G1)
Cr-Ni-Mo low-alloy steels				4340 (C1)		D6a (E1)	4340[a] (F1)	4340[b] (G1)
5Cr-Mo-V die steels	2				H-11 (D2)		H-11[a] (F2)	H-11[b] (G2)
Maraging steels	3				18Ni-Co-Mo (D3)			
Stainless Steel Alloys								
Straight-chromium grades (ferritic)	4		405 (B4)	442 (C4)				
Straight-chromium grades (martensitic)	5		410 (B5)	431 (C5)	440 (D5)		410[a] (F5)	440[a] (G5)
Precipitation-hardenable grades (martensitic and semiaustenitic)	6				17-7 PH (D6)		17-7 PH[a] (F6)	
Chromium-nickel grades (austenitic)	7				347 (D7)			
Austenitic Stainless Steel Superalloys								
Nonheat-treatable grades	8				19-9 DL (D8)	Timken 16-25-6 (E8)		
Age-hardenable grades	9				Discaloy (D9)	A-286 (E9)		

(a) Heat treated to 350-400 Bhn.
(b) Heat treated to 500 Bhn.

TABLE XL. NONSTAINLESS ALLOY STEELS AND STAINLESS STEEL ALLOYS GOVERNED BY SELECTED KEY ALLOYS

Group	Key Alloy	Representative Steels	Group	Key Alloy	Representative Steels
		Nonstainless Alloy Steels			
		Chromalloy			8640
A1		UHS 260	C1		USS Strux
(Low-alloy	A-4130	17-22 AS	(Low-alloy steels,	A-4340	AMS 6434
steels, Cr-Mo)		UCX-2	Cr-Ni-Mo)		Tricent
		Airsteel X200			Supertricent
		4140	E1	D6a	D6a
		Vascojet 1000			
D2	H-11	Potomac A	D3	18Ni-Co-Mo	18 Ni-Co-Mo
(Die steels,		Dynaflex	(Maraging		20 Ni
5 Cr-Mo-V)		Unimach 2	steels)		25 Ni
		Halcomb 218			
		Stainless Steel Alloys			
B4	405	430	B5	410	403
(Straight-chromium		446		(Straight-chromium	420
grades, ferritic)				grades, martensitic)	422
					419
C4	442	442			
(Ditto)					
		440 A			Lapelloy
D5	440 B	440 B			414
(Straight-chromium		440 C			Greek Ascoloy
grades, martensitic)					416
			C5	431	431
				(Ditto)	
		17-4 PH			
D6	17-7 PH	Stainless W	D7	347	321
(Precipitation-		PH 15-7 Mo	(Chromium-		304
hardenable grades)		AM-350	nickel grades,		316
		AM-355	austenitic)		317
					301
					201
		Austenitic Stainless Steel Superalloys			
			D9	Discaloy	Discaloy
D8	19-9 DL	17-14 Cu Mo	E9	A-286	Unitemp 212
(Nonheat-treatable		19-9 DX	(Age-hardening		17-10 P
grades)		HTX	grades)		HNM
		Armco 22-4-9			
E8	Timken 16-25-6	Timken 16-25-6			

(a) See Tables XLI to XLVI inclusive for compositions and properties.

TABLE XLI. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF Cr-Mo AND Cr-Ni-Mo LOW-ALLOY ENGINEERING STEELS[a]

Alloy	Nominal Chemical Composition, per cent										Room-Temperature Properties					Machinability Class
	C	Mn	Si	Cr	Ni	Mo	W	V	Cu	B	Usual Form(b)	Condition(c)	Strength, 1000 psi Tensile	Strength, 1000 psi Yield	Elongation, per cent	
									Cr-Mo							
4130	0.3	0.5	0.27	0.9	--	0.20	--	--	--	--	B	Ann	88	60	30	A1
	--	0.50	0.75	--	--	--	--	--	--	--		HT (400 Bhn)	214	182	15	G1
Chromalloy	0.2	*	*	1	--	1	--	0.12	--	--	B	HT	139	117	8	E1
UHS 260	0.3	1.2	1.5	1.2	--	0.35	--	0.2	--	--	B	Ann	--	--	--	A1
												HT (R_C 52)	270	230	11	G1
17-22 AS	0.3	0.5	0.65	1.2	--	0.5	--	0.25	--	--	B	Ann	--	--	--	A1
												HT (415 Bhn)	207.5	190	15	G1
UCX-2	0.39	0.7	1	1.1	--	0.25	--	0.15	1	--	--	--	--	--	--	A1
Airsteel X200	0.43	0.8	1.6	2	--	0.5	--	0.05	--	--	S	HT	246.9	204.8	11	G1
4140	0.40	0.81	0.22	0.66	0.35	0.22	--	--	--	--	B	Ann	--	--	--	A1
												HT	241	195	6	G1
									Cr-Ni-Mo							
8640	0.4	0.9	0.27	0.5	0.55	0.20	--	--	--	--	--	Ann	--	--	--	B1
USS Strux	0.43	0.87	0.65	0.9	0.75	0.52	--	0.01	--	0.0005	B	Ann	--	--	--	C1
												HT	301	251	9.0	G1
D6a	0.47	0.7	0.3	1	0.6	1	--	0.07	--	--	F	Ann	--	--	--	C1
												HT	450	325	6.0	G1
4340	0.4	0.7	0.3	0.8	1.8	0.25	--	--	--	--	B	Ann	--	--	--	C1
												HT	260	217	8	G1
AMS 6434	0.34	0.7	0.3	0.8	1.8	0.35	--	0.2	--	--	S	Ann	--	--	--	C1
												HT	255	232	12	G1
Tricent 300 M	0.43	0.8	1.6	0.85	1.8	0.4	--	0.08	--	--	B	Ann	--	--	--	C1
												HT	289	245	9.5	G1
Super Tricent	0.5	0.8	2.1	0.9	3.6	0.5	--	--	--	--	--	--	--	--	--	--

*Asterisks denote that data are unavailable.
(a) From References 9-11, 14, 16, 21, 25, 119, 124-126, 132-134.
(b) B = bar; S = sheet; F = forging.
(c) Ann = annealed; HT = heat treated.

TABLE XLII. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF 5Cr-Mo-V MEDIUM-ALLOY DIE STEELS(a)

Alloy	Nominal Chemical Composition, per cent								Room-Temperature Properties					Machinability Class
									Usual Form(b)	Condition(c)	Strength, 1000 psi		Elongation, per cent	
	C	Mn	Si	Cr	Ni	Mo	W	V			Tensile	Yield		
Peerless 56	0.4	0.6	1	3.3	--	2.8	--	0.35	S	--	--	--	--	--
Crucible 56	0.4	0.6	1	3.3	--	2.6	--	0.4	--	Ann	--	--	--	D2
										HT (R_C 53)	262.0	221.3	5	G2
								H-11						
Vascojet 1000	0.4	0.3	--	5	--	1.3	--	0.45	--	HT (R_C 33)	154	124	14.1	F2
	--	0.4	1	--	--	--	--	0.5		HT (R_C 54)	290	235	77.8	G2
Potomac A	0.4	0.3	1	5	--	1.3	--	0.5	--	--	--	--	--	--
Dynaflex	0.4	0.3	1	5	--	1.3	--	0.5	B	Ann (R_C 29)	135	100	16	D2
										HT (R_C 46)	220	190	11	G2
										HT (R_C 56)	310	250	3	G2
Unimach 1	0.35	0.45	1	5	--	1.4	--	0.45	--	--	--	--	--	--
Halcomb 218 (Crucible 218)	0.4	0.4	1	5	--	1.4	--	0.4	B	HT (R_C 53)	262.0	221.3	5	G2
								H-13						
Potomac M	0.4	0.3	1	5.25	--	1.2	--	1.0	B	HT (R_C 54)	297	226	12.5	G2
Unimach 2	0.5	0.4	1.1	5	1.4	1.3	--	1.0	B	HT (R_C 56)	305.5	280.2	7.1	G2
	--	--	1.0	5.3	1.6	--	--	--						

(a) From References 9, 11-14, 16, 24-26, 124, 126, 132, 133.
(b) S = sheet; B = bar.
(c) Ann = annealed; HT = heat treated.

TABLE XLIII. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY OF CLASSIFICATIONS OF THE 400 SERIES STAINLESS STEELS[a]

Alloy	Nominal Chemical Composition, percent[b] C	Mn	Si	Cr	Ni	Mo	W	V	S	N	Zr	Al	Cu	Usual Form[c]	Room-Temperature Properties Condition[d]	Strength, 1000 psi Tensile	Yield	Elongation, percent	Machinability Class
									Ferritic Types (Nonhardenable)										
405	0.08	1	1	13	--	--	--	--	--	--	--	0.2	--	--	Ann (150 Bhn)	70	40	30	B4
	0.12	1	1	16	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
430	0.06	--	0.3	16	--	--	--	--	--	--	--	--	--	--	Ann (155 Bhn)	75	45	30	B4
430 F	0.12	1.2	1	16	--	0.6	--	--	0.15	--	0.6	--	--	--	Ann (170 Bhn)	80	55	25	--
	0.2	1.5	1	25	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
446	0.3	1	1	--	--	--	--	--	--	0.25	--	--	--	--	Ann (170 Bhn)	80	50	25	B4
442	0.25*	1.00*	1.00*	18-23	0.50*	--	--	--	--	--	--	--	--	--	Ann (200 Bhn max.)	80	45	20	C4
									Martensitic Types (Hardenable)										
403	0.15	1	0.5	12	--	--	--	--	--	--	--	--	--	--	Ann (155 Bhn)	75	40	35	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (390 Bhn)	190	145	15	--
410	0.15	1	1	12.5	--	--	--	--	--	--	--	--	--	--	Ann (155 Bhn)	75	40	35	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (390 Bhn)	190	145	15	F5
420	0.3	1	1	13	--	--	--	--	--	--	--	--	--	--	Ann (195 Bhn)	95	50	25	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (512 Bhn)	250	215	8	--
422	0.23	0.75	0.35	12	0.8	1.0	1.0	2.5	--	--	--	--	--	S	Ann	95	64.5	25.5	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (R_C 49)	260	199	5	--
419	0.25	1	0.2	12	1	0.5	2.9	0.4	--	--	--	--	--	--	--	--	--	--	--
Lapelloy	0.3	1	0.3	11.8	0.25	2.8	--	0.25	--	--	--	--	--	B	HT (R_C 26)	125	84	20	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (R_C 45)	210	120	12.0	F5
414	0.15	1	1	12.5	1.9	--	--	--	--	--	--	--	--	--	Ann (235 Bhn)	115	90	20	--
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (410 Bhn)	200	150	15	--
AMS 5616	0.17	0.4	0.3	12.7	1.9	0.15	3	--	--	--	--	--	0.13	B	Ann (293 Bhn)	140.5	--	18	--
Greek Ascaloy	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (364 Bhn)	160	--	16	--
416	0.15	1.2	1	13	--	0.6	--	--	--	--	0.6	--	--	--	Ann (155 Bhn)	75	40	30	B5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (390 Bhn)	190	145	12	--
431	0.2	1	1	16	1.9	--	--	--	--	--	--	--	--	--	Ann (260 Bhn)	125	95	20	C5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (415 Bhn)	205	155	15	--
440A	0.67	1	1	17	0.75	--	--	--	--	--	--	--	--	--	Ann (215 Bhn)	105	60	20	D5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (510 Bhn)	260	240	5	--
B	0.85	1	1	17	--	0.75	--	--	--	--	--	--	--	--	Ann (220 Bhn)	107	62	18	D5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (555 Bhn)	280	270	3	--
C	1.1	1	1	17	--	0.75	--	--	--	--	--	--	--	--	Ann (230 Bhn)	110	65	14	D5
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	HT (500 Bhn)	285	275	2	--

(a) From References 10, 11, 15, 16, 20, 21, 23, 25, 55, 56, 126, 132-134, 137.
(b) * - maximum value.
(c) S = sheet; B = bar.
(d) Ann = annealed
HT = heat treated.

TABLE XLIV. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF THE 300 SERIES STAINLESS STEELS[a]

Alloy	Nominal Chemical Composition, percent[b]												Room-Temperature Properties				Machinability Class
														Strength, 1000 psi			
	C	Mn	Si	Cr	Ni	Mo	S	N	Ta	Cb	Ti	Zr	Condition[c]	Tensile	Yield	Elongation, percent	
321	0.08	2	1	18	10.5	--	--	--	--	--	5 x C	--	Ann (150 Bhn)	85	35	55	D7
347	0.08	2	1	18	11	--	--	--	Cb-Ta 10 x C		--	--	Ann (160 Bhn)	90	35	50	D7
304	0.08	2	1	19	10	--	--	--	--	--	--	--	Ann (150 Bhn)	85	35	60	D7
304 L	0.03*	2	1	19	10	--	--	--	--	--	--	--	Ann (180 Bhn)	70	25	40	D7
316	0.08	2	1	17	12	2.5	--	--	--	--	--	--	Ann (150 Bhn)	80	30	60	D7
317	0.08	2	1	19	13	3.5	--	--	--	--	--	--	Ann (160 Bhn)	85	40	50	D7
301	0.15	2	1	17	7	--	--	--	--	--	--	--	Ann (165 Bhn)	100	40	55	D7
														--	--	--	--
201	0.15*	6.5	1.0*	17	4.5	--	--	--	--	--	--	--	Ann (210 Bhn)	115	40	40	D7
302	0.15	2	1	18	9	--	--	0.25*	--	--	--	--	Ann (150 Bhn)	85	35	60	D7
302 B	0.15*	2*	2-3	18	9	--	--	--	--	--	--	--	Ann (180 Bhn)	80	30	40	D7
202	0.15*	8.5	1	18	5	--	--	0.25*	--	--	--	--	Ann (210 Bhn)	100	40	40	D7
303	0.15	2	1	18	9	0.6	0.15	--	--	--	--	0.6	Ann (160 Bhn)	90	35	50	D7
309	0.2	2	1	23	13.5	--	--	--	--	--	--	--	Ann (160 Bhn)	95	40	45	D7
310	0.25	2	1	25	20.5	--	--	--	--	--	--	--	Ann (185 Bhn)	95	45	50	D7

(a) From References 15, 16, 21, 25, 55, 56, 129, 132, 133, 137.
(b) * — maximum value.
(c) Ann = annealed
CW = cold worked.

TABLE XLV. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF THE PRECIPITATION-HARDENABLE STAINLESS STEELS[a]

Alloy	Nominal Chemical Composition, percent													Usual Form[b]	Room-Temperature Properties				
																Strength, 1000 psi			
	C	Mn	Si	Cr	Ni	Mo	Zr	V	Ta	Cb	Ti	Al	Other		Condition[c]	Tensile	Yield	Elongation, percent	Machinability Class
										Martensitic Types									
15-5 PH	0.07	1.0	1.0	14.75	4.5	--	--	--	0.30 Cb + Ta		--	--	3.5 Cu	B, P	Ann	175	--	--	
															H1150	145	125	15	
															H900	200	185	10	--
Almar 362	0.03	0.30	0.20	14.5	6.5	--	--	--	--	--	0.8	--	--	B	Ann	120	105	10	--
															ST	140	115	20	--
AM-363	0.05	0.30	0.15	11.5	4.5	--	--	--	--	--	10 + c	--	--	S	STA	125	110	12	
17-4 PH	0.07	1	1	17	4	--	--	--	0.3 Cb + Ta		--	--	4 Cu	B	Special HT (R_C 30)	130	100	24	D6
															H1150 (311 Bhn)	145	125	19	
															H900 (420 Bhn)	200	185	14	
Stainless W	0.12	1	1	17	7	--	--	--	--	--	1	1	0.2 N	B	Ann	135	95	8-12	D6
															STA	150[b]	130[b]	8-12	
															STA	210[a]	195[a]	8-12	
PH 13-8 Mo	0.05	--	--	13	8	2	--	--	--	--	--	1	--	B, P, F	ST	160	100	15.5	
															H1100	173	162	17.5	
															H950	215	190	16.0	
										Semiaustenitic									
PH 15-7 Mo	0.09	1	1	15	7	2.5	--	--	--	--	--	1.1	--	B	Mill ann (R_B 88)	130	55	35	D6
															T (R_C 28)	145	90	7	
															TH 1050 (R_C 44)	210	200	7	
17-7 PH	0.09	1	1	17	7	--	--	--	--	--	--	1.1	--	B	Mill ann (R_B 85)	130	40	35	D6
															T (R_C 31)	145	100	9	
															TH 1050 (R_C 43)	200	185	9	
PH 14-8 Mo	0.05	0.8	0.5	14.5	8.5	2.5	--	--	--	--	--	1.25	--	S	Mill ann (R_B 88)	125	55	25	D6
															SRH 1050 (R_C 46)	215	205	5	
															SRH 950 (R_C 49)	235	220	5	
AM-350	0.12	0.9	0.5	16.5	4.5	3	--	--	--	--	--	--	0.1 N	S	Ann	145	60	40	D6
															DA	185	150	12	
															SCT	200	172	13	
AM-355	0.15	0.95	0.5	15.5	4.5	3	--	--	--	--	--	--	0.1 N	S	Ann	185	56	30	D6
															DA	190	170	12	
															SCT	215	185	12	
										Austenitic Types									
Discaloy	0.05	0.8	0.8	0.13	26	2.5	--	--	--	--	1.7	--	--	B	STA	145	106	19	D9
A-286	0.08	1.5	0.7	14.8	26	--	--	0.3	--	--	1.2	0.35	--	B	ST (R_B 150)	--	--	--	E9
															STA (R_C 27)	146	100	25	
Unitemp 212	0.08	0.25	0.25	16	25	--	0.05	--	--	0.5	4	0.35	0.06 B	--	--	187	134	23	E9
17-10P	0.12	0.8	0.6	17	10.3	--	--	--	--	--	--	--	0.27 P	B	ST	--	--	--	
															STA (286 Bhn)	137	68	25	
															DA (302 Bhn)	143	77	20	
HNM	0.3	3.5	0.5	19	9.5	--	--	--	--	--	--	--	0.25 P	B	ST (R_B 192)	116	56	57.5	E9
															STA (R_C 38)	168	124	19.5	E9

(a) From References 10, 11, 16-22, 25, 124, 126, 131-136.
(b) B = bar; S = sheet.
(c) Ann = annealed
HT = heat treated
STA = solution treated and aged
ST = solution treated only
T = conditioned material heat to 1400 F ± 25 F, hold for 90 minutes, cool to 60 F $^{+6}_{-10}$ w/in 1 hour, hold 1/2 hour
DA = double-aged. Low temperature anneal at 1710 F; air cool; condition at 1375 F for 3 hours; air cool to room temperature; temper at 850 F for 3 hours, air cool to room temperature
SCT = subzero-cooled and tempered. Low temperature anneal; air cool to room temperature; refrigerate at -100 F, 3 hours; temper at 850 F, 3 hours; air cool to room temperature
H1050 = heat solution-treated material to 1050 F ± 10 F, hold, air cool to room temperature
H900 = solution-treated material heated at 900 F on 1 hour and air cooled
H = high-temperature annealed or solution-treated (ST)
TH = double-aged material
TH 1050 = heat annealed material to 1400 F, hold 90 minutes, cool to 60 F in 1 hr, hold at 60 F for 30 minutes, heat to 1050 F, hold 90 minutes, air cool to room-temperature
SRH = heat annealed material to 1700 F, hold 60 minutes, air cool to room temperature; cool to -100 F within 1 hour, hold for 8 hours, bring up to room temperature; heat to 950 F or 1050 F; hold 60 minutes; air cool.

TABLE XLVI. COMPOSITIONS, MECHANICAL PROPERTIES, AND MACHINABILITY CLASSIFICATIONS OF THE NONHEAT-TREATABLE STAINLESS STEEL SUPERALLOYS[a]

Alloy	Nominal Chemical Composition, percent													Room-Temperature Properties					Machinability Class
														Usual Form[b]	Condition[c]	Strength, 1000 psi		Elongation percent	
	C	Mn	Si	Cr	Ni	Mo	W	N	Ta	Cb	Ti	P	Cu			Tensile	Yield		
Carpenter 16-25-6	0.08	2	1	16	26	6	--	0.15	--	--	--	--	--	B	Ann (207 Bhn) H-CW (326 Bhn)	120 162	58 143.5	39.2 15.5	E8
Croloy 15-15N	0.15	2	0.75	15.5	15	1.5	1.4	0.1	--	Ta+Cb 1.0	--	--	--	--					
17-14 CuMo	0.12	0.75	0.5	15.9	14.1	2.5	--	--	--	0.45	0.25	--	3	B	STA	86	42	45	D8
19-9 WMo	0.1	--	--	19	9	4	1.3	--	--	4	0.35	--	--	--					
19-9 DL	0.3	1.2	0.6	19.3	9	1.3	1.3	--	--	Cb+Ta 0.4	--	--	--	B	Ann (188 Bhn) H-CW (328 Bhn)	102 154	42 125	53 24	D8
19-9 DX	0.3	1.2	0.6	19.3	9	1.5	1.3	--	--	--	0.6	--	--	B	Ann (188 Bhn) H-CW (154 Bhn)	102 154	42 125	53 24	D8
19-9 WX	0.11	1.2	0.6	21	8.5	0.5	1.6	--	--	1.3	0.2	--	--	--					
HTX	0.45	8.5	--	21	8	1.5	--	0.2	--	--	--	0.23	--	--					D8
Armco 22-4-9	0.5	7.8	0.15	20	3.2	--	--	0.35	--	--	--	--	--	--					D8
Timken 16-15-6	0.05	1.75	--	16	25	6	--	0.15	--	--	--	--	--	--					E8

(a) From References 11, 16, 17, 20-22, 25, 132-134.
(b) B = bar.
(c) Ann = annealed
H-CW = hot cold worked.
STA = solution treated and aged.

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APPROVAL

MACHINING AND GRINDING OF ULTRAHIGH-STRENGTH STEELS AND STAINLESS STEEL ALLOYS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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